Canada's Carbon Utilization Market

FORESIGHT CANADA

CANADIAN GAS ASSOCIATION
ASSOCIATION CANADIENNE DU GAZ

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About Foresight

Foresight Canada helps the world do more with less, sustainably. As Canada's largest cleantech innovation and adoption accelerator, we de-risk and simplify public and private sector adoption of the world's best clean technologies to improve productivity, profitability, and economic competitiveness, all while addressing urgent climate challenges.

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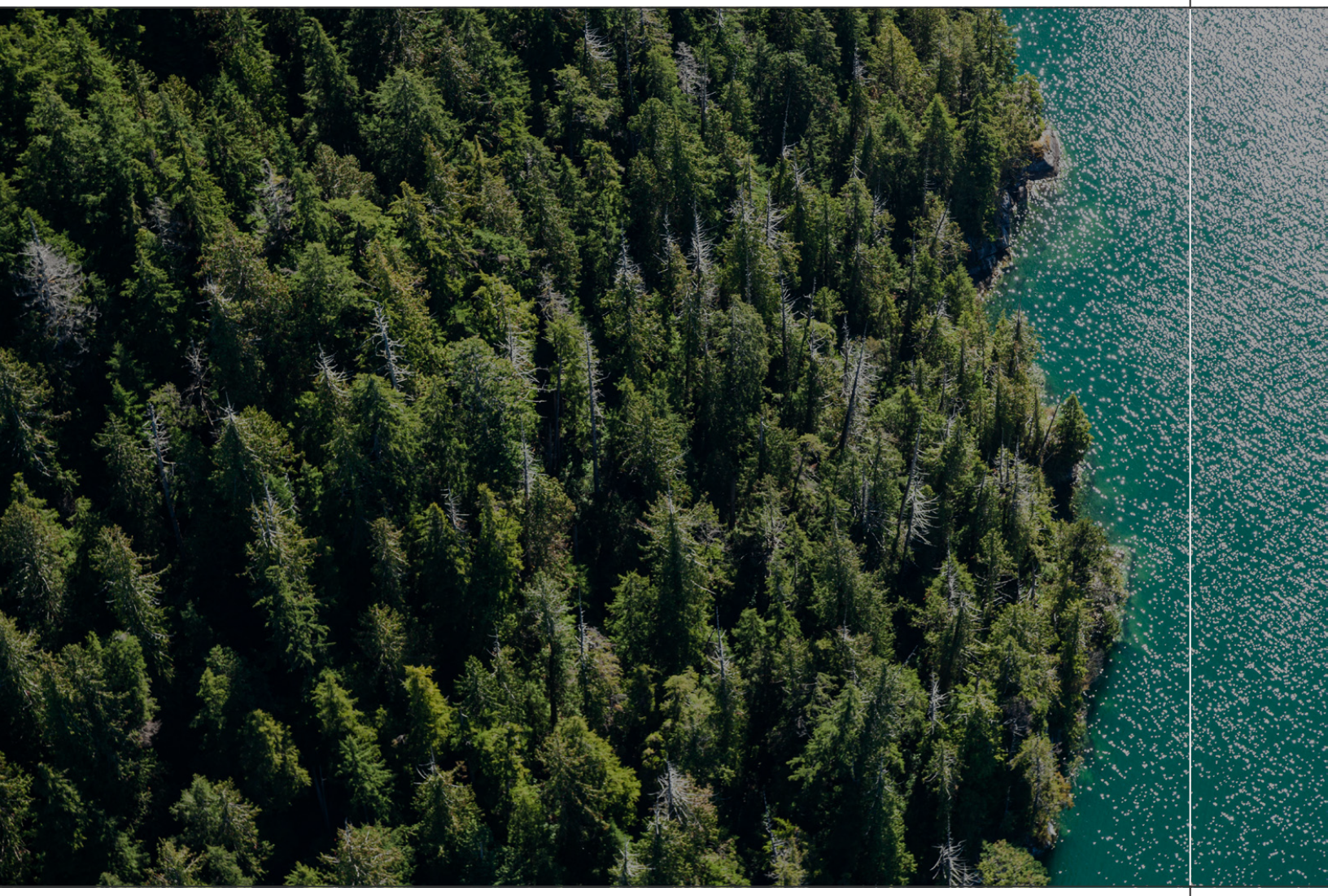

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Executive Summary

Utilizing captured CO_2 presents a promising yet nascent opportunity in Canada's journey toward reducing industrial emissions. This study aims to assess CO_2 utilization technologies based on their applicability in the Canadian market. It will ultimately provide background information for gas utilities to assess opportunities in implementing carbon capture and utilization (CCU) projects.

Market Assessment

CO_2 utilization can be approached through conversion or direct use. Approximately 230 megatonnes (Mt) of CO_2 are used globally each year, primarily in direct-use pathways. The bulk of this is for manufacturing urea (130 Mt) and enhanced oil recovery (80 Mt), with smaller amounts used in the food and beverage industry, welding, fire suppression, and other applications. There are currently 181 carbon utilization projects worldwide, including 10 in Canada.

In the short term, the market potential for CO_2-based products and services remains relatively small, largely due to high associated costs. Long-term market projections for CO_2 utilization vary, reflecting the uncertainty and early development stage of the industry.

Strategic development of CCUS hubs near large emitters is identified as a crucial step to reduce costs and facilitate industry scale-up. Regions like Southwest Ontario, which boast significant industrial clusters and lack a legislative framework for geological sequestration are highlighted as potential opportunities for CCU deployment.

Jurisdictional Scan

The USA, the Netherlands, and Australia are advancing innovative CO_2 utilization projects that offer valuable lessons for Canada.

USA:

- A collaboration between Celanese, Linde, and Mitsui in Texas is focused on producing methanol from captured CO_2 emissions and hydrogen.
- The success of this initiative is supported by the favourable regulatory environment in the US, particularly the 45Q Carbon Capture Tax Credit, which offers $82.5 per tonne of CO_2 utilized in low-carbon products.
- This project exemplifies how strategic partnerships and regulatory incentives can drive the development of low-carbon alternatives.

Netherlands:

- Twence, a major sustainable energy producer in the Netherlands, is working on a project in Hengelo to capture and utilize 100,000 tonnes of CO_2 emissions annually from waste-based energy generation.
- Twence's approach emphasizes starting with small-scale projects to gain experience before scaling up, showcasing a model of cautious but progressive development in CO_2 utilization.

Australia:

- Mineral Carbonation International (MCi) is pioneering a world-first mineral carbonation demonstration plant in Newcastle, Australia.
- MCi's strategy includes co-locating with existing infrastructure to minimize costs and creating multiple CO_2 product streams to diversify revenue.
- This project underscores the importance of co-location in reducing barriers to implementation.

Utilization Pathways

Conversion pathways transform CO_2 into useful products such as chemicals, fuels, and building materials. These processes, often referred to as 'carbontech', offer opportunities to generate revenue from CO_2-based products and potentially offset investments in CCU.

The report focuses on CO_2 utilization pathways to produce fuels, chemicals, and new materials, which represent the most commercially advanced and marketable areas within the carbontech ecosystem. Technologies for CO_2 conversion are at various stages of commercialization, with some, such as CO_2 use in concrete, ready for immediate deployment.

Fuels

- **Methanol:** Traditionally produced from fossil fuels, methanol can be synthesized using captured CO_2 and green hydrogen, resulting in low-carbon 'e-methanol'.
    - **Hydrogen in Fuel Production:** The generation of hydrogen significantly impacts the overall emissions intensity and cost of these fuels.

Chemicals

- **Ammonia to Urea:** Ammonia is an intermediate in the production of nitrogen-based fertilizer. The production of ammonia is energy-intensive, emissions-heavy, and largely driven by natural gas-based processes, and is a major target for decarbonization in the chemicals sector. Synthesizing urea from ammonia is already a large direct user of captured process CO_2. However, the process still has a positive carbon footprint.
- **Plastics and Polymers:** CO_2 can be utilized as a feedstock for producing polymers, offering a renewable alternative to fossil fuels. This approach is still in the research and demonstration phase but holds promise for future commercialization.

New Materials

- **Cement and Aggregates:** The construction industry, particularly cement production, is a significant source of CO_2 emissions. Incorporating CO_2 into the production of building materials—such as through carbonation in concrete—offers a way to sequester carbon and reduce the overall carbon footprint of construction.
- **Solid Carbon:** Produced through the partial combustion of hydrocarbons, solid carbon, or carbon black, is used in various applications including rubber reinforcement, coatings, and plastics. Emerging markets for advanced carbon products like graphite, carbon fibres and carbon nanotubes may influence future demand for carbon black; however, the commercial viability is limited as production currently exceeds demand.

Rationale for Utilization vs. Sequestration

Multiple factors come into play when carbon emitters decide to invest in CO_2 utilization or sequestration. For example:

- **Volume of Emissions:** Utilization may be more suitable for smaller-scale emissions. For large emitters, sequestration is often preferred due to its ability to handle substantial volumes of CO_2.
- **Location and Infrastructure:** Regions with established CCS infrastructure may be more likely to opt for sequestration, while areas without existing infrastructure would have to consider the substantial investment needed to develop it.
- **Geography:** Regions with limited or no proximity to geologic storage may be inclined to consider utilization opportunities as industry considers decarbonization options.
- **Transportation:** The logistics of transporting CO_2 from emission sources to utilization or sequestration sites plays a significant role in decision-making. In regions where pipeline infrastructure is limited or costly to develop, other transport modes like shipping, rail, or road may be used, impacting the overall feasibility and cost of the project.
- **Cost Considerations:** Factors such as capture, transportation, and conversion costs influence the economic feasibility of CO_2 utilization versus sequestration. Utilization can be more expensive but offers potential revenue generation through product creation, which can offset some costs. Sequestration is currently less costly but does not provide direct revenue. Developing CCUS hubs is a way of making CCUS projects more financially viable.

Life Cycle Assessment Discussion

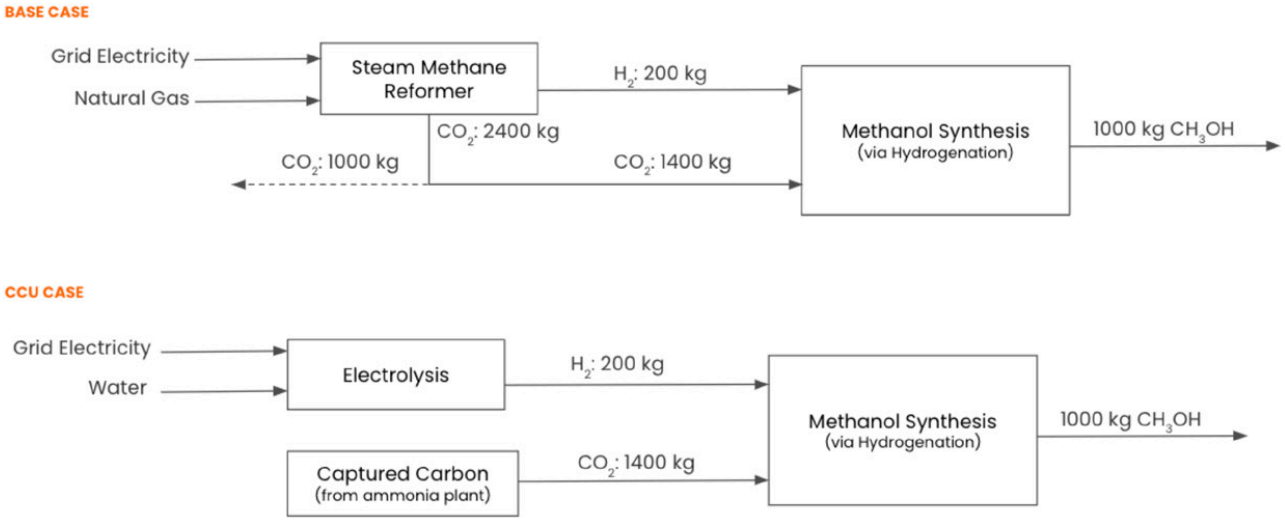
A Life Cycle Assessment (LCA) is a critical tool for evaluating the environmental impacts of processes or products from inception to disposal. In this context, an LCA aims to quantify the environmental intensity of different CO_2 utilization pathways. This discussion offers a high-level overview to provide a framework for a detailed quantitative evaluation. In contrast, detailed LCA investigations involve complex calculations on each input, process and sub-process of a wide range of inputs using emission factors from specialized databases on commercially available LCA software.

Utilization pathways transform captured CO_2 into products, which requires energy and inputs. The net carbon footprint of these products can differ significantly from that of products produced by conventional methods. In some cases, the overall life cycle carbon footprint of decarbonization pathways may be higher.

Example:

For methanol production, the comparison between conventional and CO_2-utilizing pathways shows that the production of e-methanol (produced with CO_2 and green hydrogen) can result in significantly lower carbon footprints compared to traditional fossil fuel-based methods. A simplified LCA example calculation follows for methanol production using an objective quantity of 1000 kg:

System Boundary



Base Case				
Process	**Input Flow**	**Amount**	**Unit**	**Total Emissions (kg CO_2 eq)**
SMR	Hydrogen generation via SMR [1]	200	kg H_2	2364
	Carbon capture and process utilization [2]	1400	kg CO_2	-1400
Methanol Synthesis (hydrogenation)	Hydrogenation process to produce 1000 kg methanol [3]	1000	kg CH_3OH	794
			BASE CASE TOTAL EMISSIONS	**1758.0**
CCU Case				
Process	**Input Flow**	**Amount**	**Unit**	**Total Emissions (kg CO_2 eq)**
Electrolysis	Hydrogen generation via electrolysis	200 [76]	kg H_2	434
	Capture carbon via ammonia plant	1400 [76]	kg CO_2	-1330
Methanol Synthesis (hydrogenation)	Hydrogenation process to produce 1000 kg methanol [4]	1000	kg CH_3OH	794
			CCU CASE TOTAL EMISSIONS	**-102.0**

[1] Values account for cradle to plant gate carbon intensity in the province of BC

[2] Note this is a simplified study that assumes a 100% concentrated CO2 stream that leads to a 1:1 ratio of consumption

[3] This analysis assumes the emissions intensity for methanol synthesis does not include the SMR step

[4] This analysis assumes the emissions intensity for methanol synthesis does not include the electrolysis step

An LCA provides the ability to quantify the environmental impacts of different CO_2 utilization pathways. Understanding these impacts helps in making informed decisions about CO_2 conversion technologies.

Policy Barriers and Requirements

The current policy and regulatory landscape in Canada provides a mixed but generally supportive environment for the development of CO_2 utilization technologies. Key federal and provincial initiatives highlight a strong commitment to advancing CCUS with significant investments and tax incentives designed to stimulate the early adoption and commercialization of these technologies. Key policies include:

- **Investment Tax Credit for CCUS:** This credit aims to incentivize early adoption of carbon technologies until 2030, with eligibility extending to projects that store or utilize CO_2 in Canada or the US.
- **Carbon Contracts for Difference:** These contracts de-risk investments in low-carbon industries by offsetting costs through market mechanisms, helping clean technologies compete with conventional ones.
- **Clean Fuel Regulations:** These regulations require a 15% reduction in the carbon intensity of gasoline and diesel by 2030 and establish a credit market for low-carbon fuel projects.

Additionally, the federal Carbon Management Strategy signals a growing commitment to the CCUS sector, with expected increases in targeted RD&D, policy support, and scaling efforts. Future market growth in carbon utilization is anticipated, driven by policies like Carbon Contracts for Difference (CCfDs). These mechanisms are intended to de-risk investment and can potentially enable a market for CO_2-based products. However, policy barriers and uncertainties do exist in Canada at the federal level, such as:

- **Scale-Up of Clean Energy:** Significant clean energy and transmission capacity will be necessary to support CO_2 utilization technologies. Current clean energy infrastructure may not be sufficient to meet these needs.
- **Verification of CO_2-Based Products:** The absence of standardized certification for net-zero products and limited global incentives may deter investment, as fossil fuel-based products remain cheaper.

Addressing these barriers and uncertainties is crucial for developing a robust carbon market and successfully growing CO_2 utilization technologies in Canada.

Next Steps

Utilizing CO_2 is an emerging opportunity, and the Canadian industry plays a pivotal role in advancing the sector. Amid growing pressure to decarbonize, technologies like CCUS can become an effective tool to reduce industrial emissions, particularly in hard-to-abate sectors. On the other hand, industry adoption of innovative tech is critical to the commercialization and scale-up of CO_2 utilization.

However, CCU is often perceived as a risk, and industry players can be reluctant to move forward. So, what can industry do to accelerate CO_2 utilization?

1. **Knowledge Sharing:** Often a misunderstanding of the added value of cleantech, unfamiliarity with the risks of the status quo, and a lack of expertise are contributing factors to the reluctance of adopting a solution. [1] Sharing knowledge by funding the publication of research, collaborating in networks or clusters, and attending conferences can help increase general industry familiarity with carbon technologies, and help avoid the duplication of knowledge-gathering efforts.

2. **Pilot Projects:** Conducting pilot projects can help to advance the CO2 utilization market, particularly if multiple companies are involved to lessen and/or share the risk, prove the technology, and build understanding and expertise among staff. [2]

3. **Collaboration on All Fronts:** It is widely accepted that collaborating on CCUS hub development is a way of reducing costs by enabling shared infrastructure. Increased collaboration between industry players is needed to enable the sector to grow. [2]

As Canada strives to transition to a low-carbon economy, industry's continued engagement and leadership in CO_2 utilization will be pivotal.

Introduction

As Canada intensifies its commitment to reducing greenhouse gas (GHG) emissions, the carbon dioxide (CO_2) utilization market has emerged as a critical component in transforming environmental challenges into economic opportunities. Utilizing CO_2 as a value-added product is an emerging opportunity. With its abundant natural resources and strong policy support, Canada's CO_2 utilization market is poised for growth, offering promising opportunities for economic development and climate change mitigation.

The study aims to assess CO_2 utilization technologies based on their applicability in the Canadian market. It will ultimately provide background for gas utilities to assess opportunities in implementing carbon capture and utilization (CCU) projects.

The Canadian Gas Association (CGA) members develop pathways to guide customers on GHG emissions reduction and seek to better understand the market, life cycle, and technologies that could be associated with carbon utilization. This CO_2 utilization market study will help inform future decisions on technology development strategy focus and policy engagement. It seeks to better understand how and where CO_2 utilization provides the most value with the most emissions abatement, and what action needs to be taken to develop these opportunities in Canada.

While CO_2 sequestration is being actively developed across Canada, utilization may be a viable option for some captured CO_2. To better understand the place for CO_2 use, the objective of this study is to:

- Determine the current and future projections of CO_2 utilization markets and highlight the highest impact opportunities to reduce GHG emissions
- Establish a rationale for CO_2 utilization vs. sequestration
- Understand the process for determining life cycle emissions of various utilization pathways
- Understand what policy barriers exist and what changes are needed for CO_2 utilization to occur

Market Assessment

The Market Assessment section provides an overview of the current CO_2 utilization market and its future in the short and long term.

Current Market

CO_2 can be utilized in two ways—either through conversion or direct use pathways. Each year globally, about 230 megatonnes (Mt) of CO_2 are used, predominantly in direct-use pathways. About 130 Mt is used to manufacture urea for fertilizers, and around 80 Mt is used in enhanced oil recovery (EOR). [3] Other use cases of CO_2 is in the food and beverage sector, welding, working fluids, yield boosting, and fire suppression. [4, 5]

A 2018 study indicated that globally, there were 181 carbon utilization projects, of which 10 were based in Canada. These technologies ranged from pilots to fully commercial. Of the Canadian projects, 12 per cent were mineralization and CO_2-to-solid projects, and six per cent were fuels-focused. [6] The study further reflected that Canada has the fourth-highest number of patents filed for CCS technologies after the US, China, and the EU.

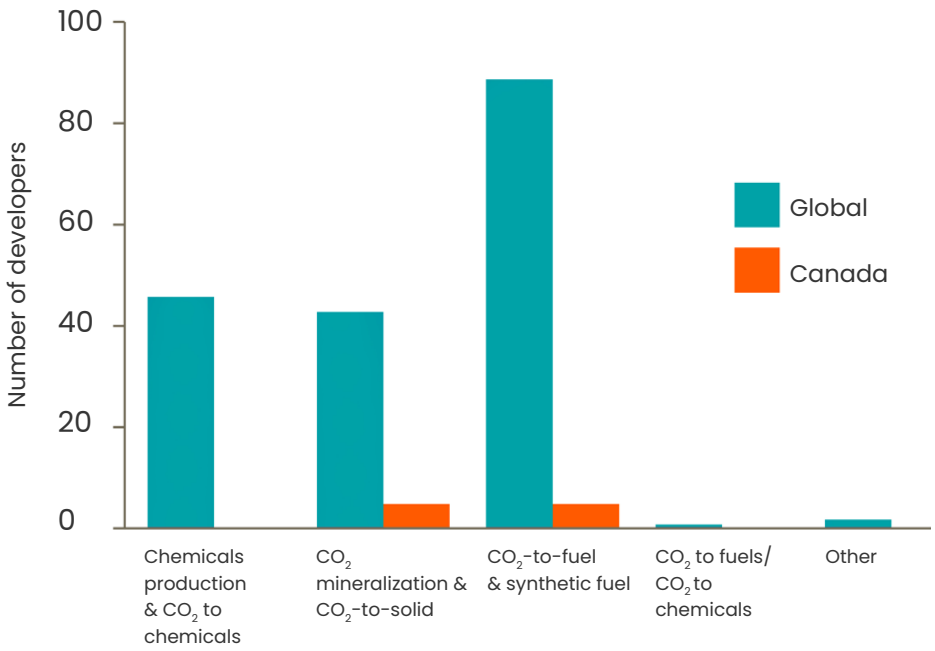


Figure 1: Canadian utilization projects by utilization pathway. [6]

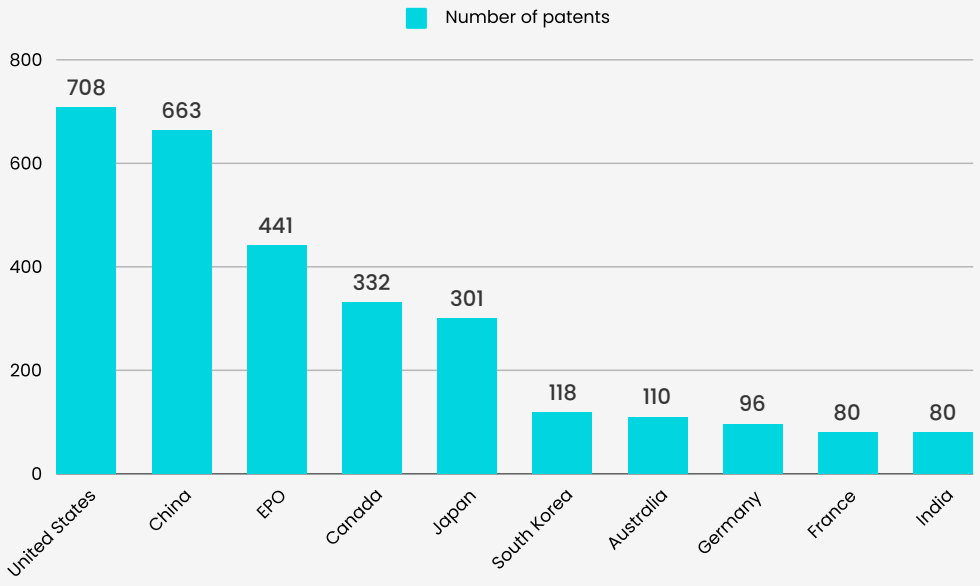


Figure 2: Top 10 countries by the number of CCS patents filed. [7]

An example of a Canadian project is discussed below:

Project CO2ment

- The project is a joint partnership between Lafarge, Svante, and Total Energies and will showcase Svante's capture technologies. It was initiated in 2019 and consists of three phases: pre-treatment, carbon capture, and utilization. [8]
- Svante's technology captures CO_2 emissions from Lafarge's plant by purifying them from flue gasses. The technology is currently in its third phase, and demonstrations are being carried out for using CO_2 in fuels, concrete, and fly ash. [9]

A 2023 report by Foresight reflected 64 carbon technology companies founded in Canada, working across the carbon value chain. 26 of these companies are in the utilization and conversion space. Of these, 13 are involved in the conversion of CO_2 to chemicals, seven in consumer products, six in building materials, six in e-fuels, and one in the food and beverage space. Globally, of 274 conversion companies, 25 were Canadian. [10]

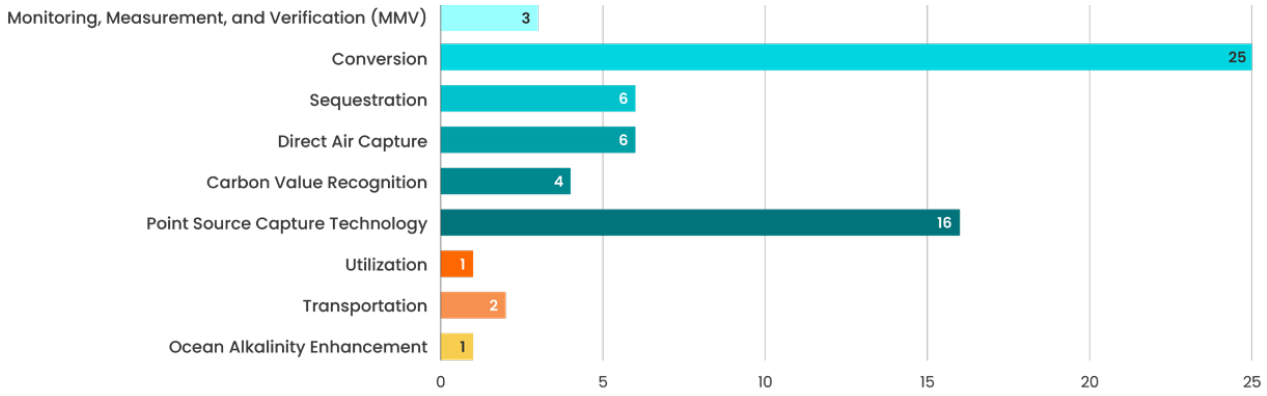


Figure 3: Distribution of carbon tech companies across the value chain processing steps. [10]

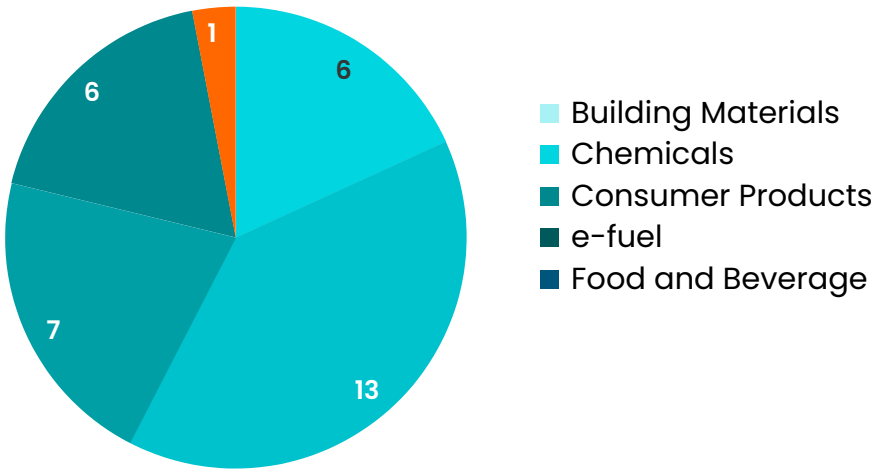


Figure 4: Classification of CCU companies by use case. [10]

Research indicates that industrial use of captured CO_2 to manufacture carbon-based products is still nascent, barring a few projects globally. The exact volumes of CO_2 being utilized in Canada is a difficult figure to validate at the current stage of the market. It is evident that although carbon utilization technologies offer strong potential for carbon emissions abatement and long-term sequestration, and the number of technologies is on the rise, the market is still evolving globally and in Canada.

Focus on Storage

The Canadian market is largely focused on carbon capture and storage (CCS) at this time. There are seven CCS projects in operation in Canada, of which most are based in the oil and gas sector. About 2.7 Mt of CO_2 equivalent gasses are captured via Canadian CCS projects based in the oil and gas sector each year. [11] Canada has five operational commercial-scale CCUS projects as of 2023, including Shell Quest, the Alberta Carbon Trunk Line (ACTL), and the Boundary Dam CCS Project. [5] Approximately 40 additional proposed carbon capture projects are in various stages of development in Canada. [12] For example, Shell wants to expand its operations by building another capture facility in Scotford named 'Polaris'. In Saskatchewan, Cenovus Energy is looking to make a facility in Lloydminster and Whitecap Resources and Federated Co-Operatives are looking to build a shared facility in Regina. Other companies such as Pathways Alliance, TC Energy, and Pembina Pipelines have proposed to develop pipelines to support carbon capture projects. [13]

Direct Air Capture (DAC) technologies are another area of CCUS in development in Canada. Leading Canadian companies like Carbon Engineering and Gaia Refinery are making an impact on the global stage as they scale technologies meant to remove CO_2 directly from the atmosphere.

Future Market

Short Term (2024-2030)

The Canadian market for CO_2 utilization is poised for some growth over the next two to five years. The growth in CO_2 utilization is being driven by several factors, including:

- Policy mechanisms to drive private and public investment such as the CCUS Investment Tax Credit (ITC), Clean Fuels Fund, and Federal Carbon Management Strategy.
- Increasing demand for emissions reductions to meet the federal emissions target of 40 per cent below 2005 levels by 2030.

In the short term, the market potential for products and services from captured CO_2 will likely remain relatively small. Early opportunities are likely to include the use of CO_2 in low-carbon building materials like concrete, with Canadian innovators like CarbonCure, Carbon Upcycling and Carbicrete leading the way. There are several recent policy instruments that may advance the commercialization of the low-carbon building materials sector (see policy barriers and requirements section).

It has been noted that future markets for the use of captured CO_2 will likely need high revenues to offset the high cost of capture and conversion. This will have to come either from product value or government policy incentives. Recent efforts by the federal government have focused on advancing research, development, and deployment (RD&D) of CCU technologies that have the potential to reduce cost, carbon intensity, energy requirements, and can permanently sequester CO_2, including Natural Resources Canada's Energy Innovation Program CCUS RD&D Call - Utilization Focus Area, which closed February 2024. [14]

At the provincial government level, a study and corresponding white paper from Alberta Innovates, InnoTech and Emissions Reduction Alberta evaluated the market potential for CCU technologies. The paper remarked on the high potential for CO_2 mineralization in concrete and noted that despite challenges with chemical conversion of CO_2, promising technologies do exist. [15]

Long Term (2030 and beyond)

Global Market

There are various projections for the long-term market for CO_2 utilization for 2030 and beyond. As a nascent industry, these numbers are market projections and vary depending on the reference.

- The **Global CO_2 Initiative** has predicted that the global market for utilization technologies will hit around $1 trillion ($8 billion USD) by 2030 [16] and it is estimated that about 7,000 Mt of CO_2 will be utilized annually in 2030. [6] On the product side, the global market for CO_2-based products is estimated to be $1.09 billion annually [6] and by 2050, the market could reach $6 trillion ($4.4 trillion USD). The table below provides a break-up of the carbon market and estimated annual CO_2 consumption: [17]

	Annual Market Opportunity ($ billions in USD)	**Annual CO_2 Consumption** (megatonnes)
Construction materials Precast concrete, aggregates	800-1,000	1000-9,500
Fuels Jet fuel, methane	21-2,060	280-10,800
Chemicals Formic acid, methanol	100-180	260-580
Pure carbon materials Carbon black	14-66	40-200
Polymers Polyurethane	130-190	2-13
Food Animal feed	18-920	5-400

Figure 5: Annual market opportunity for CO_2-based products and CO_2 consumption by 2050. [17]

- The **International Energy Agency (IEA)** indicates that based on global projects in development, about 15 Mt of CO_2 could be captured annually by 2030 for use in prominent utilization pathways including synthetic fuels, chemicals, and building aggregates. The IEA further elaborates that, of this, 8 Mt could be used to produce synthetic fuel alone. [3]
- A study by the **Oil and Gas Climate Initiative (OGCI)** and **Boston Consulting Group (BCG)** published in 2024 focuses on four high-impact use cases at the global level. These include construction aggregates, concrete, e-fuels such as e-methanol, and e-kerosene. The study further reported that the utilization market could reach 430-840 Mt by 2040. [18]
- A study by **Lux Research** indicates that the market could reach $96 billion by 2030 and up to $780 billion by 2040. [19]
- The **US Department of Energy (DOE)** has stated that North America's demand for captured CO_2 for utilization could be 40 Mt per annum by 2030 and 100-250 Mt by 2050. [20]

Interview participants noted that the market potential for carbon utilization could be driven by the demand for products like fuels, chemicals, and consumer products. It was further stated that the next two to five years could see more pilot demonstrations take place, and more widespread adoption could take 10 to 20 years. Even once the product is in the market, it is likely the customer will incur a green premium for such products, but the market size will ultimately depend on the customer and a willingness to pay a green premium.

Canadian Market

The federal government of Canada has stated that its carbon capture, utilization and storage tax credit could help abate 15 Mt of emissions. [13] The Budget 2021 proposed to reduce emissions by 15 Mt through its CCUS tax credit from projects that invest in CCUS and came into effect in 2022. [21] The government has further stated that carbon capture technologies will be crucial to help achieve net zero emissions by 2050. [13] The government is using tax incentive mechanisms to signal investors to invest in CCUS projects to achieve its climate targets. This could mean that we see a rise in carbon-based products from CCUS-based technology investments and deployments, including capture and utilization equipment.

In 2018, the Pembina Institute reported that Canada has the potential to store 22 per cent of GHG emissions through carbon utilization per annum by 2035. Based on 2017 emissions levels, this equates to approximately 165 Mt per annum (Mtpa). [6] Given that there are no more recent or detailed quantifications of the projected CO^2 utilization volumes in the Canadian market, looking at industrial emissions clusters across the country, particularly in sectors that have been noted as “hard to decarbonize”, can help indicate where potential emissions capture technologies may need to be deployed. The rationale for the use of captured CO^2 versus sequestration (discussed in Rationale section) can then aid in extrapolating potential CCU deployment opportunities. Table 1 shows notable point source emissions clusters in high-emitting sectors across the provinces under study.

Table 1: Volume of CO_2 emissions by region and industry

Province	Significant Sectoral Point Source Emissions [5]	2022 Emissions (Mt CO_2 eq) [22]	Notable Point Source Emissions Clusters [6] [22,23]	Proximity to existing CCS infrastructure [24]	Proximity to Storage Geology [24]
Ontario	Oil and Gas	8.7			
	Downstream Oil and Gas • Petroleum Refining	6.7 (6.1)	Southwest ON (Corruna, Sarnia)	none	<50 km [7]
	Upstream Oil and Gas • Oil, Natural Gas and CO_2 Transmission	2.0 (1.8)	Kenora Southwest ON (North York)	none	>50km <50 km
	Electricity	3.8	N/A		
	Heavy Industry	28.6			
	Iron and Steel	12.5	Hamilton Algoma	none	<50 km >50 km
	Chemicals and Fertilizers	6.2	Southwest ON (Sarnia, Courtright, Aylmer, Niagara Falls, Stoney Creek, Port Colborne)	none	<50 km
	Cement	4.2	Southwest ON (St. Marys), Southcentral ON (Bowmanville, Picton), Mississauga	none	<50 km

[5] For the purposes of this report, significant is defined as the 2-3 largest point source emitters by sector (significant subsectors mentioned beneath); or emissions otherwise notable for CCUS potential.

[6] Notable emissions clusters include regions of potential CCUS hubs identified by secondary sources. Clusters typically include industrial emitters in proximity to each other. This information was supplemented by federal emissions data.

[7] 50 km was chosen as an arbitrary distance to indicate close proximity based on several secondary sources. 50 km is generally accepted as a reasonable distance for a more economic pipeline to connect emissions sources to larger trunk lines or alternative storage infrastructure. [24–26]

Province	Significant Sectoral Point Source Emissions [5]	2022 Emissions (Mt CO_2 eq) [22]	Notable Point Source Emissions Clusters [6] [22,23]	Proximity to existing CCS infrastructure [24]	Proximity to Storage Geology [24]
Saskatchewan	Oil and Gas	27			
	Upstream Oil and Gas • Conventional Oil Production • Oil, Natural Gas and CO^2 Transmission • Oil Sands (Mining, In-Situ, Upgrading)	25.5 (19.8) (2.3) (2.2)	Northern Saskatchewan (Lloydminster, Onion Lake, Paradise Hill, Turtle River, Eldon, Elden) Central Saskatchewan (Maidstone, Waseca, Paynton, Meota, Vawn, Kerrobert, Unity, Cactus Lake, Kindersley, Coleville, Oakdale, Nottingham, Nether Hill, Major, Snipe Lake) Southern Saskatchewan (Stoughton, Estevan, Roche Percee, Alameda, Griffin, Carmichael, Battrum, Swift Current, Glen Ewen) Weyburn	>50 km >50 km >50 km <50 km	<50 km <50 km <50 km
	Downstream Oil and Gas • Petroleum Refining	1.5 (1.2)	Regina, Moose Jaw, Instow, Kerrobert	>50 km	<50 km
	Electricity	13.3	Regina (Estevan, Coronach, Swift Current), Saskatoon (Saskatoon, Lloydminster, North Battleford)	>50 km	<50 km
	Heavy Industry	4.2			
	Chemicals and Fertilizers	0.9	Regina (Belle Plaine), Saskatoon (Unity, Saskatoon, Lloydminster)	>50 km	<50 km
	Iron and Steel	0.1	Regina	>50 km	<50 km
Alberta	Oil and Gas	158.3			
	Upstream Oil and Gas • Oil Sands (Mining, In-Situ, Upgrading) • Natural Gas Production and Processing • Conventional Oil Production	153.6 (84.3) (45.9) (17.0)	Northern Alberta (Edmonton, Gibbons, Peace River, Fort McMurray, Grande Prairie, Wood Buffalo, Northern Lights County, Fort Saskatchewan, Bonnyville) Central Alberta (Didsbury, Rimbey, Rocky Mountain House, Edson, Caroline, Drayton Valley, Olds, Hinton, Crossfield) Southern Alberta (Cochrane, Calgary, Medicine Hat, Pincher Creek)	>50 km <50 km >50 km	<50 km <50 km <50 km
	Downstream Oil and Gas • Petroleum Refining/Upgrading	4.7 (4.4)	Northern Alberta (Edmonton, Sherwood Park, Gibbons, Slave Lake)	>50 km	<50 km

Province	Significant Sectoral Point Source Emissions [5]	2022 Emissions (Mt CO_2 eq) [22]	Notable Point Source Emissions Clusters [6] [22,23]	Proximity to existing CCS infrastructure [24]	Proximity to Storage Geology [24]
Alberta	Electricity	19.4	Northern Alberta (Edmonton, Whitecourt, Fort Saskatchewan, Fort McMurray, Fort Saskatchewan, Grande Prairie) Central Alberta (Calgary, Rocky View County, Cochrane, Kananaskis, Canmore, Seebe, Banff) Southern Alberta (Lethbridge, Taber, Fort Macleod, Carseland, Strathmore)	>50 km <50 km >50 km	<50 km <50 km <50 km
	Heavy Industry	18			
	Chemicals and Fertilizers	13.2	Sturgeon County (Gibbons, Redwater) Northern Alberta (Fort Saskatchewan, Mitsue) Wheatland County (Carseland) Lacombe County (Prentiss, Joffre) Southern Alberta (Medicine Hat)	<50 km <50 km <50 km <50 km <50 km	<50 km <50 km <50 km <50 km <50 km
	Cement	1.7	Exshaw, Edmonton	<50 km	<50 km
	Pulp and Paper	1.5	Athabasca County County of Northern Lights (Peace River) Northern Alberta (Whitecourt, Grande Prairie, Hinton, Slave Lake)	<50 km >50 km >50 km	<50 km <50 km <50 km
British Columbia	Oil and Gas	15.2			
	Upstream Oil and Gas • Natural Gas Production and Processing • Oil, Natural Gas and CO_2 Transmission	14.6 (12.6) (1.6)	Northern BC (Fort Nelson, Fort St. John, Taylor, Peace River District, Dawson Creek, Bessborough, Peace River, Groundbirch, Prince Rupert, Buick) Central BC (Pine Valley) Prince George, Prince Rupert	none	<50 km <50 km >50 km
	Downstream Oil and Gas • Petroleum Refining	0.6 (0.5)	Metro Vancouver (Burnaby, Port Moody) Prince George	none	>50 km >50 km
	Heavy Industry	5.2			
	Pulp and Paper	2	Northern BC (Prince George, Quesnel) Central BC (Kamloops, Skookumchuck) Southern BC (Castlegar, Port Mellon) Vancouver Island (Nanaimo, Crofton)	none	>50 km >50 km >50 km >50 km
	Cement	1.2	Richmond	none	>50 km

Notable Opportunities in Canada: Ontario

As can be seen in Table 1, Ontario has significant sectoral point-source emissions in the southwest of the province, largely due to a petrochemical/chemical manufacturing hub stretching from Sarnia to Toronto to Kingston.

Ontario also has a well-established R&D and innovation cluster. [27] There are several carbon technology companies in the province, most of which are focused on carbon utilization technologies. This possibly stems from a number of universities focused on innovation-based research in addressing complex technology issues. [28]

Ontario has recently lifted a ban on geological carbon sequestration and is developing a legislative framework for projects. [29] Once the framework is released, pilot project testing, demonstration, and commercial-scale projects will be allowed. [30] Though this is a step forward to sequestration, it will take time to establish.

The absence of a legislative framework around sequestration, the presence of several high emitting industries needing to mitigate CO_2, a well-established R&D and innovation landscape, and a strong chemical sector that may indicate end-use potential may provide a rationale for the exploration of carbon utilization opportunities.

Jurisdictional Scan

This section spotlights three jurisdictions—the US, the Netherlands, and Australia—that are developing exemplary CO_2 utilization projects and showcases lessons that could be applied in the Canadian context.

USA

Project Summary

Celanese, Linde, and Mitsui are working to produce methanol from captured CO_2 emissions and hydrogen. Linde is already supplying Celanese with carbon monoxide, oxygen, and nitrogen from its Clear Lake facility in Texas via the Gulf Coast pipeline. The existing project expands this, where Celanese will capture and utilize CO_2 from the same Clear Lake facility that manufactures carbon monoxide and hydrogen. [31, 32] Celanese will then use the captured CO_2 emissions and hydrogen to produce methanol at its Fairway Methanol LLC JV with Mitsui & Co Ltd. [31]

Linde is an industrial gas and engineering company that serves various chemicals, energy, food and beverage, manufacturing, and mining markets. [31] Celanese is a chemicals and specialty materials manufacturing company with a wide variety of applications across major industries. [32] This tie-up showcases how different emitters are collaborating to leverage existing facilities, knowledge, and infrastructure to produce low-carbon alternatives.

Under the project, 130,000 tonnes of methanol will be produced from 180,000 tonnes of captured CO_2 industrial emissions. [32]

Best Practices

Taking advantage of favourable regulatory and policy incentive mechanisms

45Q Carbon Capture Tax Credit: Projects that capture and either store or utilize carbon dioxide from the atmosphere or industrial emissions are eligible for this US federal tax credit. Industrial emissions that are captured for use in low carbon-based products like chemicals, fuels, and building materials are eligible for $82.5 per tonne of tax credit. [33]

Clean Fuels & Products Shot: Projects that utilize CO_2 in synthetic fuels could receive more support under this regulation. [3]

Netherlands

Project Summary

Twence is in the business of sustainable energy generation and is the largest producer in the Overijessel region of the Netherlands. Although the energy is mainly generated from waste sources like non-recyclable residual and industrial waste, [34] this produces associated emissions.

Through the CCU project in Hengelo, Twence aims to capture and utilize 100,000 tonnes of CO_2 emissions from energy generation per year. Twence is one of the largest emitters in the region, emitting close to 250,000 tonnes of CO_2 emissions from fossil fuel-based sources, and this step is crucial for decarbonizing. [34] They are looking to convert the captured CO_2 into chemicals like sodium bicarbonate and liquid CO_2 for use in greenhouses. They are also considering applications in the food & beverage industry, construction materials, chemicals, and biofuels.

Best Practices

Building collaborations

Twence took a collaborative approach to developing this project, building partnerships with academic and other institutions such as the TNO, partaking in domestic and international research projects like Horizon 2020, ACT-CCS, and MOOI.

Starting small

Beginning with executing small-scale and pilot projects have helped Twence gain experience in the sector and build capacity for the execution of larger, commercial-scale operations. [34]

Australia

Project Summary

Cleantech developer Mineral Carbonation International (MCi) is developing a mineral carbonation demonstration plant, which is the first of its kind in the world in Newcastle, Australia. The MCi plant will have access to 250,000 tonnes of CO_2 emissions from Orica's Kooragang Island industrial site, which includes ammonia, nitric acid, and ammonium nitrate production facilities. [35] The captured carbon will be converted into advanced manufacturing and consumer products. [36]

MCi will utilize the emissions to convert CO_2 into carbonates using a proprietary "carbon engineering process." Carbonates can then be used to manufacture chemicals, construction materials like cement and concrete, and consumer products. Once the plant is set up, it could have the potential to scale up to a megatonne scale and be suited to other industries. [36]

Best Practices

Co-location with existing infrastructure

The MCi plant is built on Orica's Kooragang Island site, providing direct access to a significant amount of captured CO_2, minimizing transportation barriers and industrial land sourcing. MCi's process is also agnostic to the CO_2 source and can utilize a variety of CO_2 streams, including directly captured flue gas. This allows for flexibility in implementation. [37]

Multiple CO_2 product streams

MCi focuses on creating multiple value-added low-carbon and negative emissions materials that can be used in construction and manufacturing. This provides a foundation for multiple revenue streams in diverse industries to offset production costs. [37]

Utilization Pathways

CO_2 emissions can be used in two ways—direct use or conversion, which entails the chemical conversion of CO_2 into useful products in fuels, consumer goods, and building materials. An array of different CO_2 uses has led to the creation of the 'carbontech' ecosystem consisting of carbon-based products and carbon technologies. [38] Depending on who the emitters and utilizers are, the revenue generated from CO_2-based products can help recoup the investments made in carbon capture and utilization technologies. While the permanence associated with the use cases of CO_2 varies (discussed in the following subsections), it still enables low-emission alternatives for a net zero economy. [38]

Utilizing CO_2 emissions to generate valuable products will help reuse emissions generated from hard-to-abate industries. This could help achieve emission targets, recover investment costs, and decide on strategy overall.

Based on the two kinds of CO_2 usage processes: direct use includes utilization for solvents, food products, yield boosting, working fluids, and other miscellaneous uses, and conversion includes utilization for chemicals, fuels, and materials. A snapshot of the more detailed use cases of the CO_2 can be seen in Figure 8.

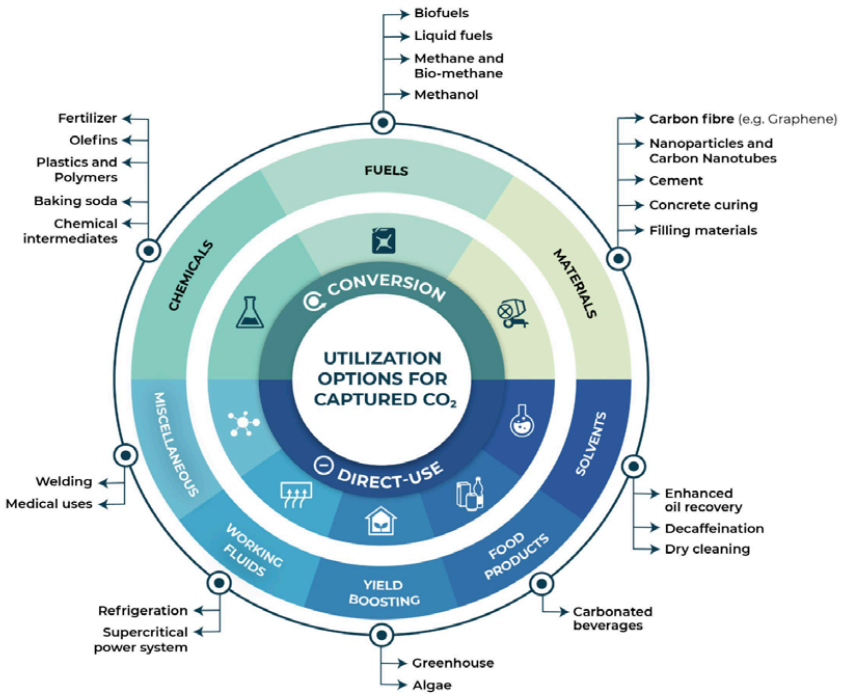


Figure 6: The different uses of CO_2, both direct use and conversion, are indicated in the chart (from Natural Resources Canada). [5]

This section outlines the different CO_2 utilization options, focusing on fuels, chemicals, and new material processes and discusses the level of commercialization for each. These utilization products are widely characterized as having the greatest market size and potential. In general, these process technologies and inputs are furthest along the commercialization path for low-carbon production. Cursory mention of other emerging technologies is provided; however, many have not yet been commercially demonstrated. It further discusses the rationale for utilization vs. sequestration in Canada. Finally, a framework and methodology for life cycle assessment calculations is discussed.

Fuels

Whereas fuels are traditionally derived from fossil fuels, CO_2 utilization pathways using clean hydrogen present an option to create low-carbon fuels.

Methanol

Hydrogen and CO_2–both needed for methanol production–have traditionally been fossil-fuel-based or generated through fossil-fuel-intensive processes, which are correlated with substantial emissions. The energy transition drive is to move from high to low carbon-intensity methanol.

Figure 7 below contrasts the incumbent fossil-fuel-based process for methanol production (grey-highlighted route) where CO_2 feedstock is derived largely from natural gas. Coal gasification is also a common process input in other parts of the world but is not discussed here. The low-carbon alternative is broadly mapped (green-highlighted) where CO_2 feedstock is renewable, from either biomass or direct air capture (DAC). Whereas the fossil-fuel-based process is CO_2 emitting, the decarbonized process is net CO_2 neutral.

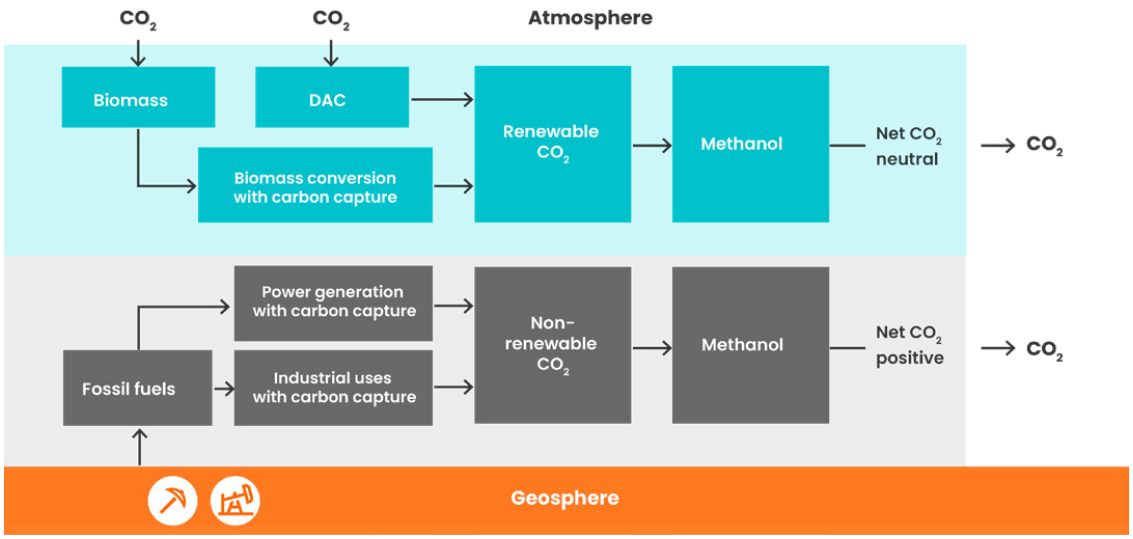


Figure 7: Non-renewable vs renewable methanol production [39]

Referring specifically to low-carbon emergent methods of methanol production, the outputs are most often referred to as 'e-methanol'—produced from green hydrogen (from renewable electricity) and captured carbon dioxide.

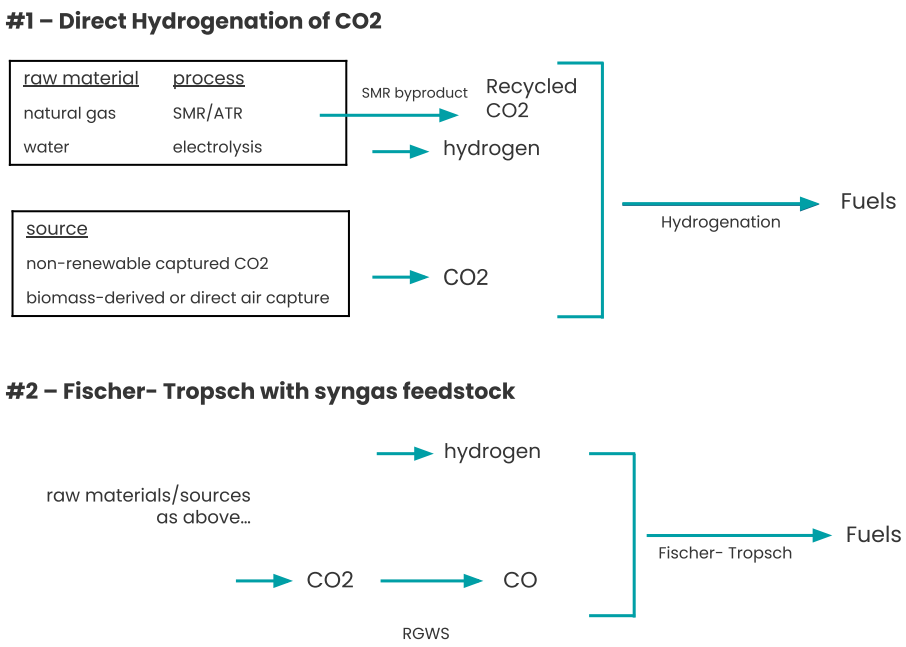
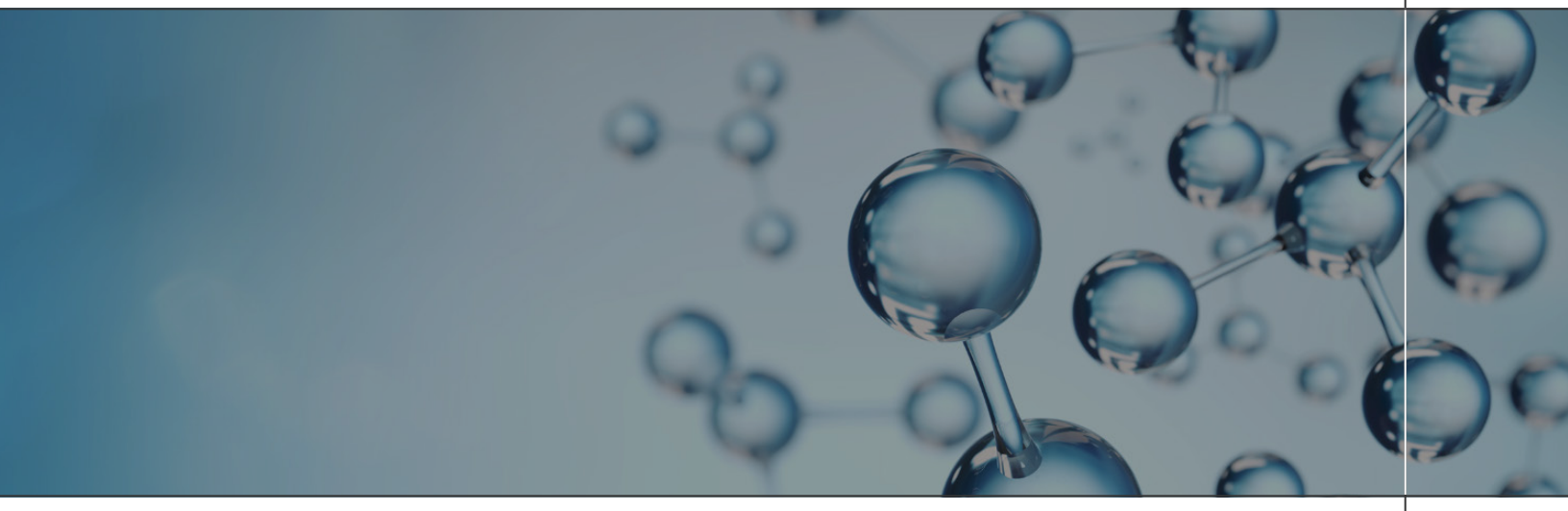


Figure 8: Methanol production pathways

Process #1 is the direct hydrogenation of CO_2 with hydrogen—a one-step process. The advantage of hydrogen generation via steam methane reforming is that the post-combustion by-product CO_2 is reused in methanol synthesis.

Process #2 is a two-step process in which syngas is produced as an intermediate step via reverse gas-water shift (RGWS) and then reduced further using hydrogen in a final step to generate fuel. Syngas is usually a mixture of carbon monoxide (CO) and hydrogen, and while it is shown here as an intermediate step to fuel production, it is marketable in some cases as a fuel itself.



Box 1: Methanol LCA calculation from Natural Resources Canada (NRCan): [8]

A comprehensive LCA was completed comparing the electricity carbon intensities of various provinces with various combinations of methanol production processes. The table below reproduces a subset of this data, selecting the provinces with the highest industrial activity. [40]

Methanol Emissions Intensity in AB, ON, BC

			Associated GHG Emissions (kg CO_2 eq./kWh)		
Production Process	**Feedstock Description**		**AB**	**ON**	**BC**
	*Depends on grid mix in each province	Electricity inputs	0.68	0.04	0.03
CO_2 Hydrogenation	Mixture of CO_2 and high-purity H_2	Methanol product	6.50	-0.90	-1.00
Conventional	Natural gas with steam methane reforming	Methanol product	0.60	0.60	0.40

[8] Note: emissions intensity may vary slightly depending on source

Hydrogen in Fuel Production

- The process of generating hydrogen as a feedstock for use in these fuel production pathways has considerable influence on the emissions footprint and overall cost of the fuel.
- Traditional processes to produce hydrogen include SMR, autothermal reforming (ATR) and coal gasification, all of which use fossil-fuel feedstock.
- An alternative production pathway is electrolysis. Electrolysis requires significant electricity and can also have high carbon intensity if the electricity is derived from fossil fuels. Electrolysis powered by renewable energy is the path to generating hydrogen with much lower emissions, however, is more costly.
- Average costs from data indicate that the cost of green hydrogen is approximately 82 per cent of the total cost of e-methanol synthesis. Another study indicates that due to current production costs for renewable electricity, green hydrogen generation can account for between 40-70 per cent of the entire production costs for methanol. [41]

Impact of Electricity

- Overall GHG emissions have a strong dependence on electricity generation.
- For example, Alberta's electricity is predominantly fossil-fuel-derived, whereas Ontario and BC largely rely on renewables.
- The CO2 hydrogenation process has a much higher reliance on electricity inputs. Thus, in Alberta where the generation mix is predominantly sourced from fossil fuel, methanol production via CO2 hydrogenation has high GHG emissions at 6.5 kg CO_2 eq/kWh, whereas conventional methane reforming has a much smaller carbon footprint (see Box 1).
- Alternatively, Ontario and BC's electricity generation mix is dominated by renewables, thus the two provinces have lower carbon footprints.
- Because conventional methanol production requires a small amount of electricity, it results in similar emissions profiles for the three provinces.

Chemicals

The carbon in CO_2 substitutes for fossil fuels in the production of chemicals, including plastics, fibres, and rubber. CO_2-derived fuels can be subsequently converted to valuable chemical intermediates such as olefins and aromatics, which are used to manufacture materials for a range of industrial sectors.

Ammonia to Urea

Ammonia is a key intermediate product in nitrogen-based fertilizers. It requires CO_2 to upgrade to urea, the main product. Ammonia production is an energy-intensive and emissions-heavy endeavour. Just over 70 per cent is produced globally via natural gas through SMR, while the bulk of the remainder is via coal gasification. The use of coal for ammonia production is restricted mainly to China, thus will not be covered in this discussion. In the fertilizer industry, ammonia production accounts for approximately 90 per cent of the total energy consumption. As is discussed in the methanol section, the energy demands of hydrogen generation are a large influence on the overall CO_2 emissions of ammonia production.

The bar chart in Figure 9 illustrates that according to IEA's Global Technology Roadmap for ammonia production, ammonia is nearly twice as emissions-intensive as crude steel production and four times that of cement, on a direct (Scope 1) CO_2 emission basis. [42] In Canada, eight out of the nine nitrogen-based production facilities use natural gas with SMR to produce the needed hydrogen. As such it is the largest target for decarbonization in the chemicals market sector. [43]

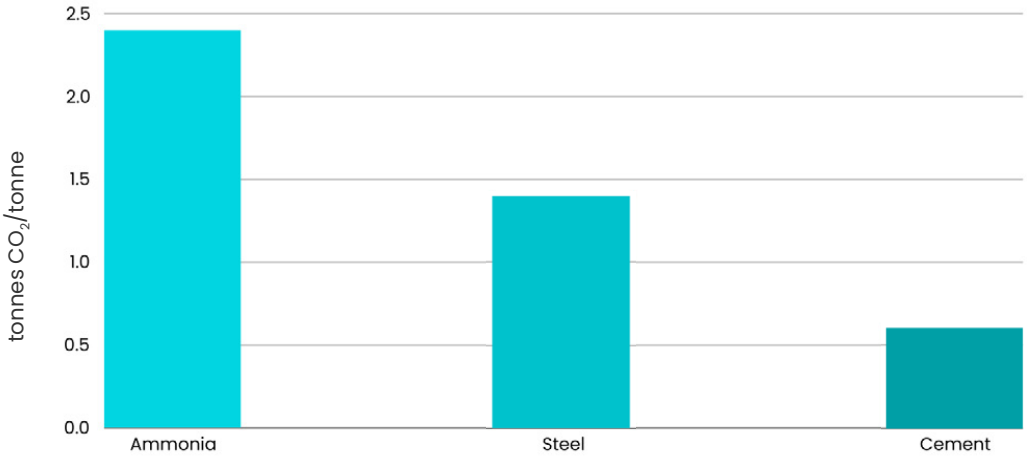


Figure 9: Emissions intensity of ammonia [42]

A simplified process flow for ammonia-to-urea is provided for both the conventional fossil-fuel-derived method and with low-carbon inputs.

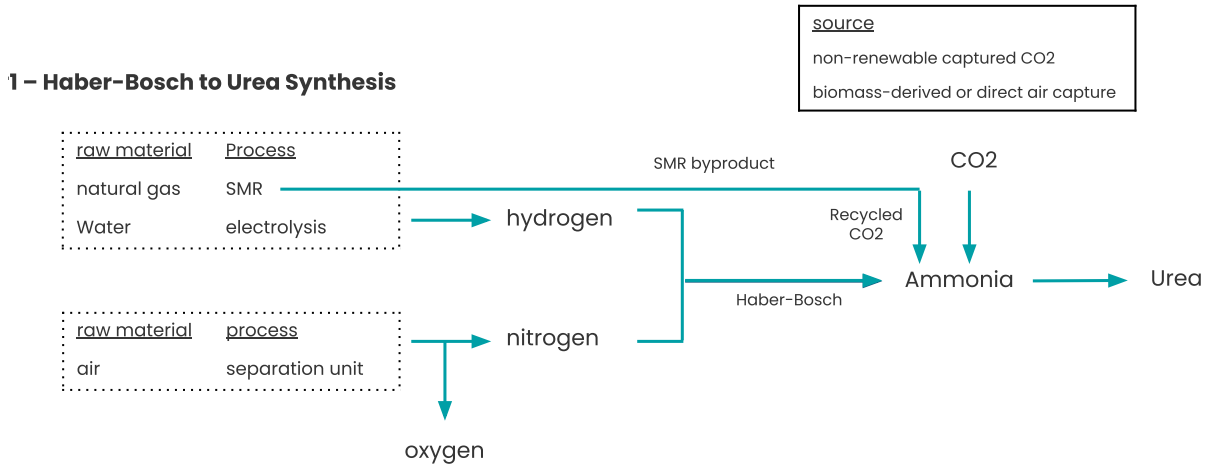


Figure 10: Ammonia to urea synthesis

In general, CO_2 is regarded as a troublesome waste product of energy consumption. However, in some circumstances it is a value-added commodity and is an established input to some industrial processes (as well as food/beverage). The largest direct use of CO_2 is in urea production—approximately 130 megatonnes (Mt) per year.

As with e-methanol production, green hydrogen inputs pose a significant barrier to making ammonia less carbon-intensive. Urea plants consume approximately 0.75 tonnes of CO_2 per tonne of urea produced. Typically, CO_2 from SMR is looped into ammonia processes on-site. Regardless, the production process emits 2.27 tonnes of CO_2e per tonne of CO_2 utilization—a net positive emission footprint over the entire life cycle. [44]

According to the Ammonia Technology Roadmap, ammonia production via methane pyrolysis with natural gas feedstock, and geologic storage for associated emissions, is furthest along towards commercial implementation in all three countries in North America—tending to be in areas with low natural gas costs and appropriate geologic storage. [42]

Plastics and Polymers

It is difficult to decarbonize the plastics sector because carbon derived from hydrocarbons is a main component of its structure. The possibility of large-scale utilization of CO_2 as a carbon feedstock is one avenue for a renewable, sustainable plastics industry and has been the source of academic investigation for some time.

An advantage of utilizing CO_2 to create polymers is that it is not particularly energy-intensive since CO_2 is converted into a carbonate, a lower-energy state molecule. Additionally, CO_2 can be stored in masses ranging from approximately 20 – 40 weight percentage (wt%) of the polymer. [45]

Most commonly, CO_2 utilization occurs in the polymerization stage to create synthetic polycarbonates such as polypropylene carbonate (PPC) and polyethylene carbonate (PEC). Alternatively, CO_2 can be used in a more indirect manner to create chemical compounds like methanol and urea to generate polymer intermediates like ethylene and propylene. These can be transformed into plastic products such as urea-formaldehyde or melamine-formaldehyde resins. In this way, captured CO_2 can act as an alternative to fossil fuel feedstock. [4]

There is a wide array of processes, chemicals and polymer intermediates for CO_2 transformation into plastics. CO_2 utilization in polymer production is still in research and demonstration stages, but there is promising laboratory research to support the view that the process could be industrially feasible and represent a promising decarbonization pathway.

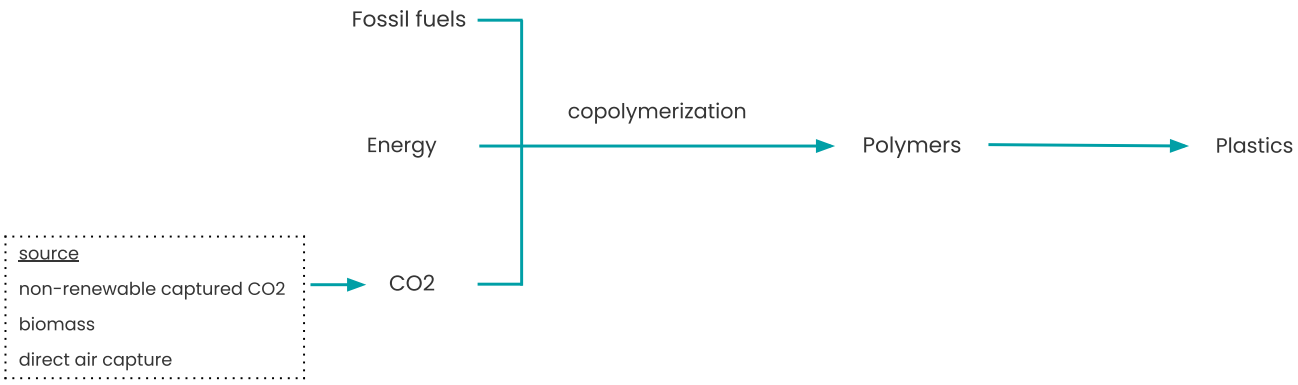


Figure 11: Polymer and plastic production process using CO_2

New Materials

The production of building materials can be achieved by reacting CO_2 with various minerals and waste products to form the carbonates required. CO_2 can also be used directly as a raw material in cement and other construction aggregates to aid in the production of building materials. Through carbonation, waste CO_2 is injected and permanently embedded in concrete during the curing process, reducing the amount of cement required.

Cement and Aggregate

Concrete is the most used building material in the world and is composed of aggregates that are bound together by cement and water. Two mechanisms can be implemented to incorporate CO_2 into the production of building materials including 1) directly adding CO_2 to concrete during the curing step where CO_2 replaces water in concrete, and 2) using CO_2 as a raw material and reacting it with waste materials/minerals (from industrial processes) to create cement and aggregates via carbonation. [4]

Steel slag, cement kiln dust, and fly ash are available waste materials that react with CO_2. These methods require using reacting elements such as calcium and magnesium with CO_2 to form carbonate molecules that can be used as aggregates in cement. CO_2-cured concrete is the most evolved and mature process and offsets emissions by reducing the amount of cement required for concrete therefore minimizing cement production. The need for carbon-containing raw materials and high-temperature requirements makes the reduction of emissions difficult.

The cement industry is the second largest industrial CO_2 emitter and contributes to around 70 per cent of all emissions associated with concrete. The main emission-intensive stages during cement production include the burning of fuel for heat generation and the calcination process where calcium carbonate ($CaCO_3$) breaks down to CaO and CO_2. During this process, clinker, the primary ingredient in cement, is created by heating $CaCO_3$ in a kiln to trigger calcination to derive lime (CaO), the primary component in cement. [46] Temperatures between 1,500-2,000 °C are achieved and CO_2 is released as a by-product. Methods to reduce emissions involve replacing fossil fuels with alternative heat sources such as waste-derived fuels. Alternatively, using less clinker by incorporating concrete mixes that use lower-carbon supplementary cementitious materials (SCMs) or utilizing Portland-limestone cement that has a higher composition of unprocessed limestone ($CaCO_3$) is most effective.

Utilizing Portland-limestone cement reduces emissions by up to 10 per cent. An average of 20 per cent of CO_2 emitted from calcination can be permanently sequestered when a concrete structure has been built. An important note is that commercial carbon capture and storage devices can capture 90-95 per cent of CO_2 emissions from the kiln used in cement production. [47]

Example project:

CarbonCure's technology enables the injection of captured CO_2 into concrete during mixing, causing a reaction that creates a mineral that becomes permanently sequestered. CO_2 mineralization allows for the optimization of cement in concrete, resulting in climate benefits.

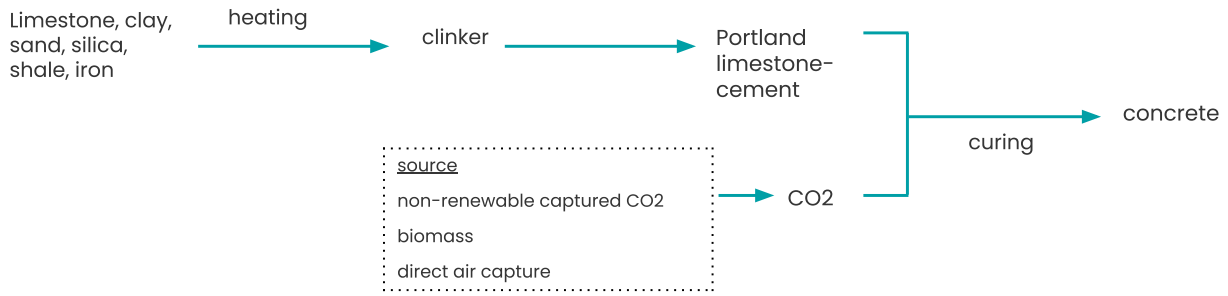


Figure 12: Low-carbon concrete production

Solid Carbon

Hydrogen gas and solid carbon residue are produced through the partial combustion of hydrocarbons. Known as carbon black, it is currently used as a rubber reinforcement in tires, in the manufacturing of coatings, plastics, and inks, to stabilize UV in pipe, cabling, and automotive components, and for pigmentation and mechanical rubber. The hydrocarbon feedstock can range from natural gas to heavy oil, necessitating adjustments in the thermal process.

The methane pyrolysis process is an emerging alternative to combustion involving the thermal decomposition of methane to its constituent parts. While hydrocarbons are the established source of methane feedstock, a low-carbon renewable feedstock can be used—renewable biogas. Renewable biogas is possible from sources such as municipal solid waste, landfills, and agricultural and forestry residues. Using biogas feedstock, methane pyrolysis can become a low-emission hydrogen and carbon black production process as there are no CO_2 emissions associated with this.

Of the two coproducts, hydrogen output is of much higher value than carbon black. Of disadvantage, the 1:3 mass ratio of H_2 to solid carbon produced, the resulting quantities of carbon black are well in excess of the current global market size. [48] Emerging markets for graphite (i.e. as a component in fuel cells), carbon nanotubes (CNTs) and carbon fibres may positively influence demand in time, but currently, there is little market potential to increase production of carbon black. Using ammonia production as an example, if there were a complete shift to methane pyrolysis to generate all the hydrogen needed for ammonia, the co-production of carbon black would be about six times what is needed globally. [42]

Commercialization of CO_2 Utilization Pathways

Typically, the commercialization process of a technology is classified into five steps—basic research or concept, feasibility research, technology development, technology demonstration or commissioning, and deployment based on the **Technology Readiness Level** (TRL). [49] The Federal Government of Canada has further developed what each level of technology readiness corresponds to, one being least ready to nine being fully deployed. [50] More details of the commercialization process of technologies corresponding to the TRL can be found in Figure 13 below.

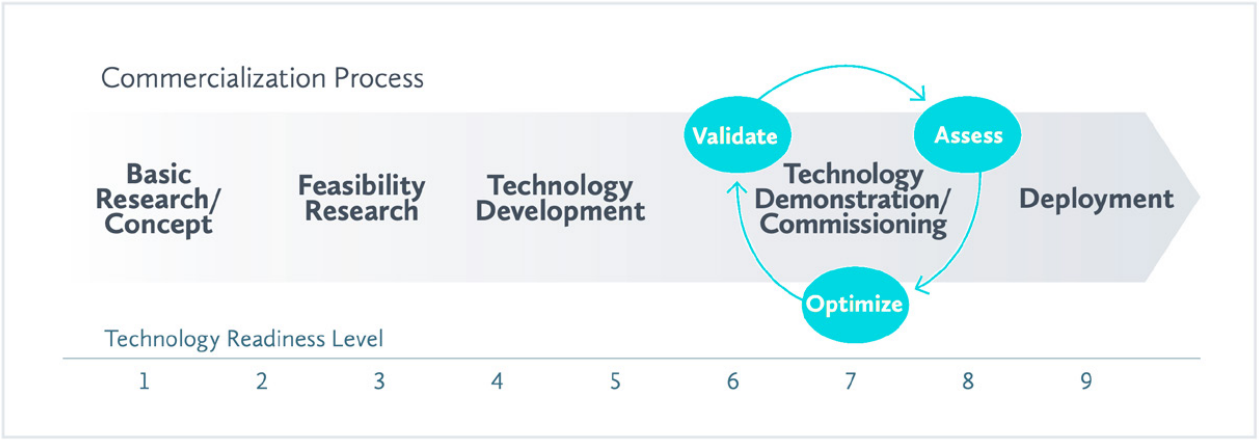


Figure 13: Commercialization process of technologies. [49]

Based on the Federal Government of Canada's categorization of the technology commercialization process, Table 2 demonstrates the commercialization stage of carbon conversion technologies.

Table 2: Table demonstrating different stages of the commercialization process of carbon utilization technologies

Category of Usage	Sub-Category	TRL	Level of Commercialization
Chemicals	Formic Acid	TRL 1-6	R&D and Technology Development [6]
	Carbonate chemicals	TRL 6 [49]	Technology Development
	Polymer and chemical feedstock	TRL 7-8	Scale-up and early commercialization [6]
Fuels	Methanol Production	TRL 7-8	Scale-up and early commercialization [6]
Materials	Carbon Nano-fibre	TRL 5-6 [49]	Technology Development
	Carbon Nanotubes	TRL 7-8 [49]	Technology Demonstration / Commissioning
	Mineralization in fly-ash	TRL 7 [49]	Technology Demonstration / Commissioning
	Carbon Mineralization	TRL 7-8	Scale-up and early commercialization [6]
	Mineralization in concrete	TRL 9 [49]	Deployment
	Concrete curing	TRL 9	Commercial [6]

Rationale for Utilization vs Sequestration

Multiple factors come into play when carbon emitters decide to invest in carbon utilization or sequestration. Factors like the volume of emissions, location, geography, transport, and costs have a bearing. The following subsection discusses some of the factors that decision-makers should consider.

Volume of Emissions

The volume of CO_2 emissions plays a significant role in determining the net benefit offered in either utilization or sequestration. Some of these factors for consideration are discussed below:

- **Storage Capacity:** Carbon sequestration can handle much larger volumes of emissions compared to most utilization options. This makes sequestration more suitable for high-volume emitters. Studies have indicated that the available global geological storage capacity of 1 terra tonne is far higher than needed to meet emissions reduction targets. In comparison, utilization can handle much lower volumes of carbon emissions. CCS may be a more viable option for large volumes of carbon storage when the emission reduction targets are high in a short period. [51]
- **Limitations in the Mtarket:** The utilization market is not expected to grow significantly in the short term, and despite the benefits utilization offers, the immediate need to reduce emissions exceeds the current capacity of CCU. [52]

One interview participant suggested that for large volumes of emissions, sequestration is considered to be the most viable option, and carbon utilization is an appropriate fit for small-scale emissions. Another interview participant noted that provinces like Alberta that have higher quantities of emissions and sequestration potential will, naturally, opt for sequestration, and provinces like Ontario where there are high volumes of emissions but minimal sequestration opportunities, may consider utilization.

Location and Infrastructure

There are a number of existing sequestration and pipeline facilities in Canada that offer geological storage of captured emissions:

- One such facility is the Alberta Carbon Trunk Line, which captures emissions from a fertilizer plant and refinery and hauls them to an oil reserve 240 kilometres south. It is said to be transporting 1.6 Mt of emissions per year, however, it has the potential to haul 14.6 Mt per year. [13] The project transports emissions from Redwater and Sturgeon down south for EOR, and in the future, has the potential to connect to other emitters in the region. In terms of the capacity of emissions hauled, it could be one of the largest CCS projects in the world. [53]

- The Alberta Carbon Grid (ACG) is another leading CCUS project at a global level targeted at emitters in the Alberta Industrial Heartland to sequester carbon in a safe, cost-effective, and reliable way. The project is being developed in phases and once developed will have the potential to sequester 10 Mt of CO_2 annually. [54] The Alberta Industrial Heartland covers regions of Fort Saskatchewan, Edmonton, and the counties of Lamont, Strathcona, and Sturgeon. [55]

The presence of established CCS infrastructure and regulations in provinces like Alberta suggest an advantage for sequestration compared to other provinces like Ontario where substantial investments in infrastructure would have to be made.

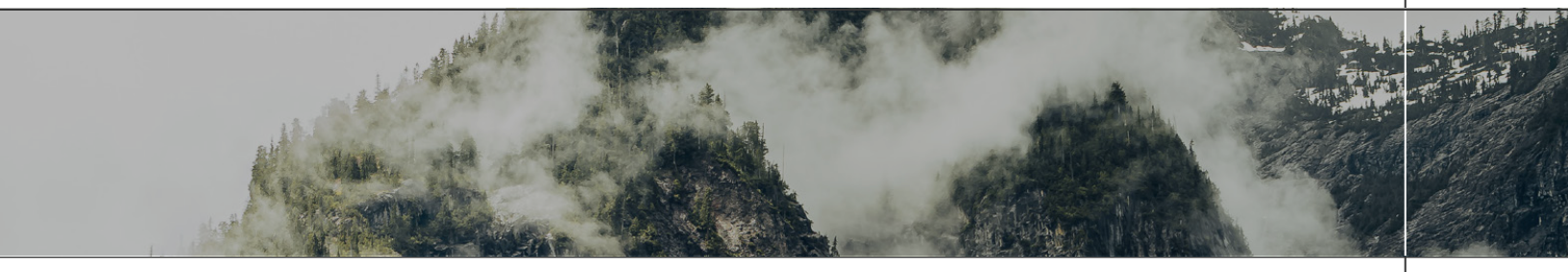
Geography

The emitter's location and the availability and proximity to geological storage may also factor into the decision of whether carbon is utilized or sequestered. It is estimated that Canada has the potential to store 398,000 Mt of emissions in geological formations. 390,000 Mt can be stored in the Western Canada-Alberta and Williston basins, and 8,000 Mt can be stored in the Quebec and Michigan basins. The Western Canada-Alberta and Williston basins in Alberta and Saskatchewan offer the best storage potential. Southern Ontario also offers potential storage options, especially in the region between Lake Huron and Erie, and is estimated to be about 850 Mt. [56] These regions in Canada offer geological sequestration for carbon emissions, with some areas already being used.

Transportation Considerations

The distance and the available mode of transport between the emitter and the utilizer can also be considered for decision-making purposes. Pipelines, both onshore and offshore, and shipping are the most technologically advanced modes of transportation, and transport by rail and road are not as preferred, especially for CCS projects where large volumes are transported. [57]

Additionally, the type of available transportation infrastructure in a given region and the feasibility of transporting CO_2 in a given region play a role. For example, an interview participant expressed the challenges associated with building pipeline infrastructure in urban areas like the Lower Mainland region of BC. Given that pipeline infrastructure can be an issue in densely populated urban areas, other forms of transport like highways and railroads would need to be used, which would have additional cost, regulatory, and safety considerations.



Cost

Cost is a crucial factor in determining the feasibility of CO_2 utilization vs sequestration, and many factors play a role. In any given region, the policy landscape, market demand, and the previously discussed factors (emissions volume, location and infrastructure, and transportation) will have an impact on the cost of carbon abatement. It is important to note that most cost estimates available today come from modelling studies deploying assumptions due to the limited number of CCUS facilities in operation.

The cost of carbon capture is generally the highest in the CCUS process due to the energy and equipment demands of separating CO_2 from other compounds in a gas stream. This cost fluctuates depending on the concentration of the gas mixture, and is generally higher the lower the concentration of CO_2. [58] According to a study by the International Institute of Sustainable Development (IISD), carbon capture costs are estimated to range from CAD $27–48/t$CO_2$ captured for concentrated CO_2 streams to CAD $50–150/t$CO_2$ captured for diluted gas streams. [59] Note these ranges do not include the cost of transportation and storage.

In utilization, a significant amount of energy is required to capture and convert captured CO_2 molecules into carbon-based products. This supplied energy has to be from a clean or renewable source to have a net benefit on the climate, which has associated costs. [20] A big factor in the economics of CO_2 utilization is the cost of hydrogen, which is often needed in conversion reactions. However, the economic incentive attached to the final products of CO_2 utilization, which provide added value and can scale with time, is a potential method of regaining some of the costs. A 2019 study published in Nature modelled a projection of the costs of various CO_2 utilization pathways, and estimated ranges as follows: [60]

- **Chemicals** (methanol, urea, polymers): USD $-80-300/t$CO_2$ (CAD $-110-410/t$CO_2$)
- **Fuels** (methanol): Up to USD $670/t$CO_2$ (up to CAD $920/t$CO_2$)
- **Cement and aggregates:** USD $-30-70/t$CO_2$ (CAD $-40-100/t$CO_2$)

The associated costs for sequestration are also quite high and can be prohibitive in certain regions, especially if infrastructure must be built. There are also costs to CCS beyond the storage itself, including transportation of CO_2 and ongoing measuring, monitoring, and verification of geological storage. For example, an interview participant noted that for this reason, some industries are considering carbon utilization in Australia. The IEA reports that the cost of onshore pipeline transport ranges from USD $2-14/t$CO_2$ (CAD $3-19/t$CO_2$) in the US and conventional geologic storage ranges from USD $2-11/t$CO_2$ (CAD $3-15/t$CO_2$). [5,61]

At current market prices, CCS is, in general, more economical than CCU, especially if existing infrastructure can be used. It is widely accepted that creating CCUS hubs is a way of making CCUS projects more financially viable by providing a platform for shared infrastructure and transportation costs and increase economies-of-scale. [62]

Life Cycle Assessment Discussion

Life Cycle Assessment (LCA) is a technique used to evaluate the environmental impacts of a process or product throughout its entire life cycle by assessing the energy and materials inputs and outputs to compare the net CO_2 benefit. This LCA discussion will profile the implications of various utilization pathways for captured CO_2 in the context of carbon footprint and emissions intensity.

The objective of this LCA discussion is to provide a framework for a quantitative evaluation of the environmental intensity that different CO_2 conversion strategies have throughout select stages of the product life cycle. The LCA framework provides a high-level view of this process. In contrast, detailed LCA investigations involve complex calculations on each input, process, and sub-process of a wide range of inputs using emission factors from specialized commercial databases on commercially available LCA software, conducted by those with process engineering expertise. Examples of LCA software include GHGenius, GaBi, Argonne National Laboratory's GREET Lifecycle Model as well as some freeware tools.

Utilization pathways that result in CO_2-containing products, just as with established methods to create the same products, necessitate the consumption of energy and materials. When compared to traditional incumbent means to generate these same products, the comparative difference can be communicated in terms of net carbon footprint. In some cases, the decarbonization pathway can result in a greater carbon footprint in the context of an entire life cycle analysis.

LCA Parameters

System Boundaries

System boundaries are well-defined limits within a product's life where the impact of inputs and outputs are analyzed. A full life cycle for a product generated using CO_2 conversion methods with energy inputs from a variety of sources includes raw material extraction through to processing, CO_2 capture, conversion and transport to end user and/or end of life. A full-spectrum analysis is referred to as 'cradle-to-grave'. Refer to Figure 10 for a flow chart depicting the various stages.

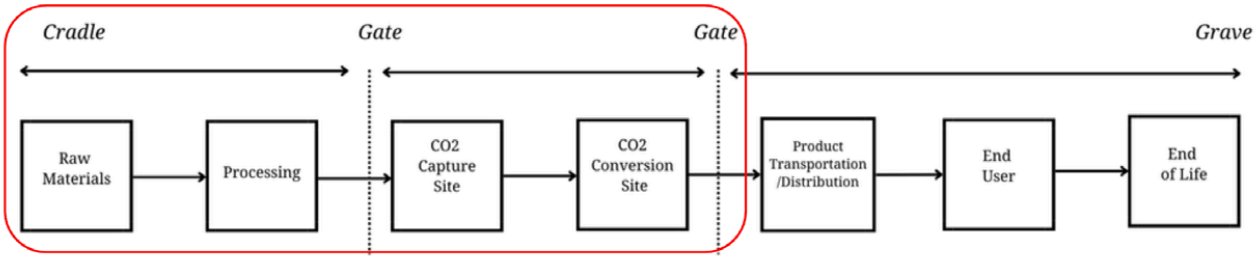


Figure 14: Diagram depicting cradle-to-conversion system boundaries

The system boundaries covered in this report, shown within the red box, are referred to as "cradle-to-plant gate" for the selected utilization pathways.

Emissions associated with the following stages are accounted for:

- **Origin:** raw material feedstock for power generation or other process inputs
- **Capture:** CO_2 capture and processing/purification
- **Transport:** if capture is not co-located with the conversion site
- **Conversion process:** includes energy inputs, feedstocks, (i.e. hydrogen) and other process inputs (i.e. catalysts, solvents)
- **Finished product:** CO_2-containing fuels, chemicals, and new materials; market ready

It is assumed that capture is co-located with the conversion site, although transport emission factors are provided and can be easily added to a carbon footprint calculation. Post-gate stages associated with 1) product transportation/distribution emissions, 2) end-user consumption of the utilization products (e.g., burning low-carbon fuel or using fertilizers for agricultural use), or 3) end-of-life aspects such as recycling or disposal are not in the defined system boundary.

Permanence

In the context of CO_2 utilization, the term 'sequestration' refers to the ability of CO_2 to stay in its final product form. This should not be confused with permanent sequestration in underground, geologic formations.

For example, low-emission fuels produced by a low-carbon utilization pathway are only temporarily sequestered because they emit CO_2 when used. Although the fuels are burned, the CO_2 conversion processes involved in their production avoid emissions associated with the extraction and processing of fossil fuels—thus, there may be fewer CO_2 emissions over the entire life cycle.

CO_2-containing concrete is (essentially) a permanent form of sequestration, as are carbon fibre and nanotubes. In cases where the end use is considered permanent, there are no emissions past the conversion stage to account for. In other cases, there can be influences from various end-of-life considerations. For example, a durable, CO_2-containing plastic may be used for decades vs incinerated or landfilled after short-term use. These factors must be considered, as they will dictate which emissions factors should be included in the LCA.

GHG Emission Metrics

- **Functional units** are described in the international LCA standard ISO 14040/44 as the "quantified performance of a product system for use as a reference unit". They are used in LCAs to standardize metrics and allow for objective comparisons of emerging low-carbon pathways to well-established methods of producing the same product. In other words, functional units enable the quantification of environmental impacts. An example of a functional unit would be 1 kilowatt hour (kWh).
- **Carbon intensity (CI)** is expressed in kilograms of CO_2 equivalent (kg CO_2eq) per functional unit produced. Example: kg CO_2eq / kWh
- **Carbon footprint** refers to the total amount of carbon emissions through all steps, accounting for feedstock material and energy inputs along the production pathway of a final product. GHG emissions are presented per kg of final product and are highly dependent on the production pathway. For example: kg CO_2 eq/kg product
- **Emissions factors (EFs)** are used to convert activities into a quantity of GHG. They are ratios that express estimated emissions of GHGs due to a given unit of activity. Examples are:
  - kilograms of CO_2 equivalent per kilowatt hour of electricity (kg CO_2 eq/kWh)
  - kilograms of CO_2 equivalent per kilogram of product (kg CO_2 eq/kg product)
- **Global Warming Potential** of different GHGs is used to calculate carbon dioxide equivalent (CO_2 eq) values enabling comparison and evaluation of emissions. GWPs are set for each GHG over a 100-year time horizon. GWPs are always expressed relative to CO_2, which is the most abundant GHG. Where CO_2 has a GWP = 1, other GHGs methane and nitrous oxide (N2O) (the second and third most abundant GHGs in the atmosphere) and have GWPs that are 28 and 265 times the polluting capacity of CO_2. [63] Typically, CO_2 eq values account for CO_2, methane and N_2O and unless otherwise stated, this is the approach taken in this report.

LCA Framework

Emission Factors and Carbon Intensities

Depending on the data source, emissions factors are derived largely from public and not-for-profit science-based organizations, examples of which are listed below:

- National (i.e. Canadian organizations like Environment and Climate Change Canada, National Inventory Report and select industry associations)
- North American (i.e. National Renewable Energy Laboratory (NREL)
- Global in the case of the International Energy Agency (IEA) or the Intergovernmental Panel on Climate Change (IPCC)
- Academic literature where LCA studies are focused on specific, jurisdictional industrial activities

Table 3 lists data pulled from the disparate sources listed above. Some difficulty was encountered in pegging the system boundaries encompassed by the factors. This was ill-defined from some of the data sources and therefore some level of uncertainty exists on what industrial steps are included. Contextually, the emission factors seem consistent with expectations when used in LCA calculations, and an example calculation is provided for methanol. Data sources are provided in the last column for reader reference in greater detail. Table 3 contains factors which form the framework enabling LCA calculations of the emissions associated with a given process.

Table 3: Emission Factors Data Table

Conversion Pathway	Utilization Product	Description	Units	Emission Factors / Carbon Intensities	Reference
OUTPUTS					
Fuel/ Chemical	Methanol	Fossil fuel	kg CO_2eq/ kg CH3OH	0.790	ECCC, 2024d [64]
	Methanol	Renewable methanol (bio / photovoltaic/solar)	kg CO_2eq/ kg CH3OH	0.090	Methanol Institute, 2022 [65]
	Hydrogen*	SMR (no CCS)	kg CO_2eq/ kg H_2	12.34	Carbon solutions, 2022 [66]
	Hydrogen*	SMR (CCS)	kg CO_2eq/ kg H_2	1.46	Carbon solutions, 2022 [66]
	Hydrogen	Fossil-fuel/SMR with 60% CO_2 recycle	kg CO_2eq/ kg H_2	3.6	IEA, 2023 [67]
	Hydrogen*	Electrolysis (renewables)	kg CO_2eq/ kg H_2	1.05	Carbon solutions, 2022 [66]
Chemical	Ammonia	Natural gas SMR process	kg CO_2eq/kg ammonia	1.80	IEA, 2021 [42]
	Ammonia	Electrolysis/biomass gasification/ methane pyrolysis	kg CO_2eq/kg ammonia	0.0	IEA, 2021 [42]
	Ammonia	Methane pyrolysis	kg CO_2eq/kg ammonia	0.0	IEA, 2021 [42]
	Urea	Bulk of nitrogen-based fertilizer	kg CO_2eq/ kg urea	0.733	ECCC, 2024c [64]
	Polymers/ Plastics [1]		kg CO_2eq/ kg product	0.9312	ECCC, 2024d [64]
Materials	Cement	Production of clinker for cement	kg CO_2eq/ kg clinker	0.5326	ECCC, 2024b [68]
	Carbon Black (solid carbon)	Production and use of mineral product	kg CO_2eq/ kg carbon	0.044	ECCC, 2024d [64]
INPUTS					
	Electricity Alberta	Provincial grid	kg CO_2eq/kWh	0.628	ECCC, 2023 [69]
	Electricity ON	Provincial grid	kg CO_2eq/kWh	0.046	ECCC, 2023 [69]
	Electricity BC	Provincial grid	kg CO_2eq/kWh	0.040	ECCC, 2023 [69]

Conversion Pathway	Utilization Product	Description	Units	Emission Factors / Carbon Intensities	Reference
INPUTS					
	Solar Voltaic + storage (global)	Global	kg CO_2eq/kWh	0.035	Raugei et al, 2020 [70]
	Nuclear (global)	Uranium	kg CO_2eq/kWh	0.0028	
	Municipal water		kg CO_2eq/ m^3 H_2O	0.32	Winnipeg [71]
	Carbon dioxide	Captured CO_2 from ammonia plant	kg CO_2	-0.95[3]	Müller et al, 2020 [72]
Fuel/ Chemical Intermediate	Hydrogen generation	Fossil-fuel/SMR (60% capture rate)	kg CO_2eq/ kg H_2	5.48[4]	CICE, 2023 [73]
	Hydrogen generation	Fossil-fuel/SMR (no capture)	kg CO_2eq/ kg H_2	11.82[4]	CICE, 2023 [73]
	Hydrogen generation	Methane pyrolysis	kg CO_2eq/ kg H_2	2.84[4]	CICE, 2023 [73]
	Hydrogen generation	Renewable with electrolyzer (PEM)	kg CO_2eq/ kg H_2	2.17[4]	CICE, 2023 [73]
Upstream inputs	Natural Gas AB	marketable gas (combustion)	kg CO_2eq/m^3	1.962	ECCC, 2024a [74]
	Natural Gas ON	Combustion of marketable gas	kg CO_2eq/m^3	1.921	ECCC, 2024a [74]
	Natural Gas BC	Combustion of marketable gas	kg CO_2eq/m^3	1.966	ECCC, 2024a [74]
	Natural Gas	Feedstock	kg CO_2eq/m^3	0.246	Ecoinvent, 2021 [75]

1. Petrochemical products ethylene, ethylene oxide and styrene are only accounted for
2. *upstream/midstream emissions included in hydrogen production emission factors
3. Value includes cradle-to-gate boundary; excludes transport
4. Assumes high heating value (HHV) of hydrogen in conversion from reference value; 1 kg H_2 = 39.4 kWh

Emission factors related to coal-derived energy are not included in Table 3. This is predominantly relevant to fuels/chemicals production in China and is associated with considerably larger carbon footprints than would be found in Canada. Emissions factors for consumer end use of utilization products (e.g., fuels/chemicals) are also not provided as these would be outside the stated system boundaries of this report.

LCA Calculation Methodology

As stated in the definition of LCA, material and energy inputs must be accounted for in the calculation of total GHG emissions from the CO_2-containing product.

A generalized calculation for carbon footprint (GHG emissions) is as follows:

$$\text{GHG emissions (kg } CO_2 \text{ eq)} = \Sigma\,(EF \times C_{output}) \times GWP + \Sigma\,(CI \times C_{input}) \times GWP$$

EF: emission factor for a given mass or volume of feedstock, including intermediates of a multi-step process

C: consumption of a given mass, volume, or energy

CI: carbon intensity of energy inputs,

GWP: global warming potential of the greenhouse gas, usually expressed as CO_2 equivalent

In the generic formula above, simplified energy and material inputs are shown–more comprehensive calculations might include emissions from additional inputs such as water, wastewater and transport. In addition, LCA calculations must account for engineering processes that generate two or more products, as is the case with methane pyrolysis which produces hydrogen as well as carbon black. Process efficiencies, such as the implementation of a CO_2 recycle loop, will increase CO_2 conversion percentages and reduce net emissions. In these cases, the net effect and allocations of emissions will need to be accounted for.

LCA Example Calculations

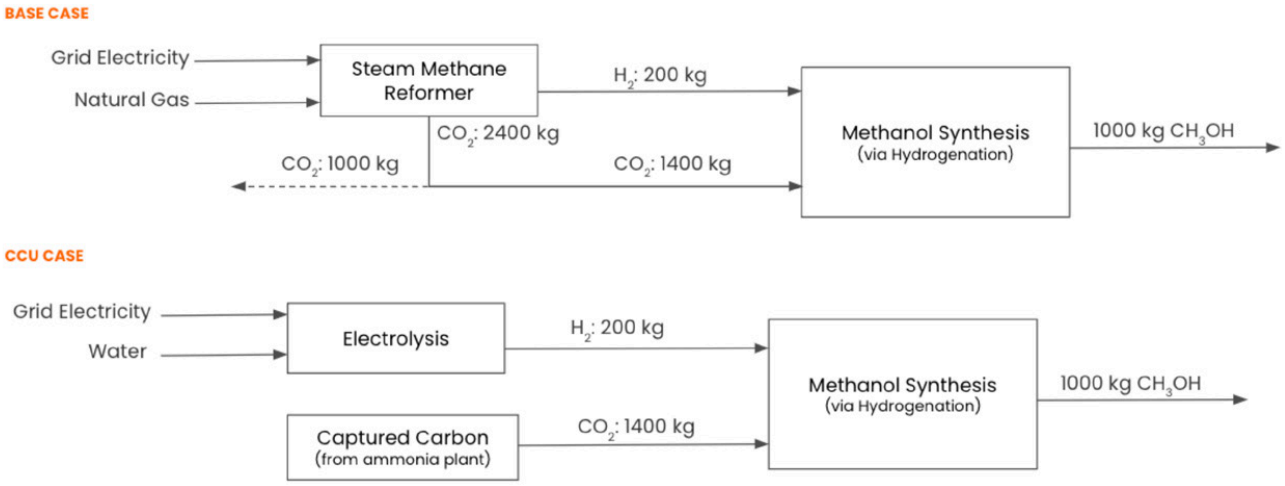
A simple LCA example calculation follows for methanol production using an objective quantity of 1000 kg.

The base case uses natural gas as feedstock, processed through steam methane reformation (SMR). The resulting hydrogen, and a portion of the output CO_2 exhaust is used for methanol synthesis through hydrogenation.

The utilization case shows grid electricity providing energy to an electrolyzer to generate hydrogen for methanol synthesis through hydrogenation. In this case, the CO_2 required for the process comes from external sources. For the purposes of this example, we have shown the use of captured CO_2 from an ammonia plant.

The emissions intensity/carbon intensity values used in the calculations can be found in Table 3. All quantities used are approximations gathered from secondary sources. Where applicable, values related to the province of BC were chosen.

System Boundary



Base Case				
Process	**Input Flow**	**Amount**	**Unit**	**Total Emissions (kg CO_2 eq)**
SMR	Hydrogen generation via SMR [9]	200 [76]	kg H_2	2364
	Carbon capture and process utilization [10]	1400	kg CO_2	-1400
Methanol Synthesis (hydrogenation)	Hydrogenation process to produce 1000 kg methanol [11]	1000	kg CH_3OH	794
			BASE CASE TOTAL EMISSIONS	**1758.0**

CCU Case				
Process	**Input Flow**	**Amount**	**Unit**	**Total Emissions (kg CO_2 eq)**
Electrolysis	Hydrogen generation via electrolysis	200 [76]	kg H_2	434
	Capture carbon via ammonia plant	1400 [76]	kg CO_2	-1330
Methanol Synthesis (hydrogenation)	Hydrogenation process to produce 1000 kg methanol [12]	1000	kg CH_3OH	794
			CCU CASE TOTAL EMISSIONS	**-102.0**

[9] Values account for cradle to plant gate carbon intensity in the province of BC

[10] Note this is a simplified study that assumes a 100% concentrated CO2 stream that leads to a 1:1 ratio of consumption

[11] This analysis assumes the emissions intensity for methanol synthesis does not include the SMR step

[12] This analysis assumes the emissions intensity for methanol synthesis does not include the electrolysis step

The carbon footprint for methanol synthesis using emissions factors for energy and material inputs given above is simplistic but illustrative. The CCU case demonstrates approximately -102 kg CO_2 eq. total emissions in comparison to 1758 kg CO_2 eq. in the base case. A detailed calculation using data from specific processes is required for a more accurate LCA.

Transport

Table 4 below provides the carbon intensities associated with different modes of transportation. The transport of various products is accounted for, including natural gas, renewable natural gas, hydrogen, and feedstocks. Fuel consumption is directly correlated with mass transported and distance travelled, therefore the unit given is the amount of CO_2 emissions over the transport of one tonne of feedstock or fuel per kilometre.

Table 4: Carbon intensities of transportation modes [77]

Type	Process	Carbon Intensity (CO_2 eq/tkm)
Generic transport	Pipeline transport of gas	117.75 g CO_2 eq/tkm
Natural gas transport	Pipeline transport of RNG	19 g CO_2 eq/tkm
Generic transport	Train transport, diesel	15.2 g CO_2 eq/tkm
Hydrogen transport	Truck transport of gaseous hydrogen	2350.47 g CO_2 eq/tkm
Hydrogen transport	Truck transport of liquid hydrogen	673.78 g CO_2 eq/tkm
Natural gas transport	Truck transport of liquid RNG	184.43 g CO_2 eq/tkm

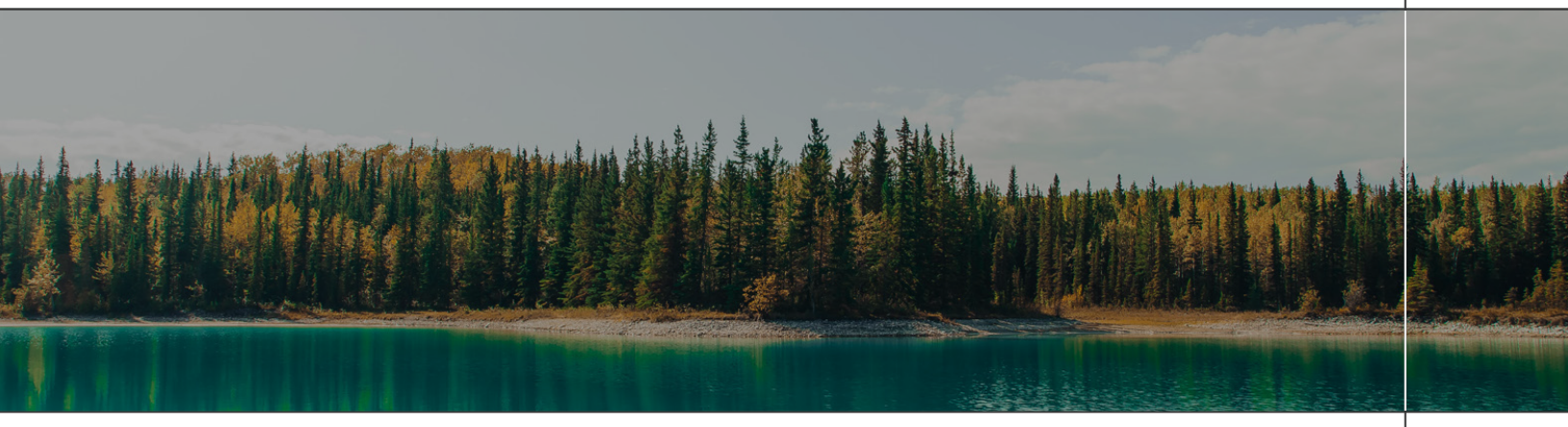
Example Calculation

Methane pyrolysis is an emerging solution to BC's need for low-cost, low-carbon hydrogen production. The 2024 report by the BC Center for Innovation and Clean Energy (CICE) on The Potential for Methane Pyrolysis in BC explores various scenarios of hydrogen production and decarbonization methods, including electrolysis and pyrolysis, in BC along with transportation methods. These scenarios are used for the following examples of transportation-associated emissions: [78]

- Scenario 1 represents a small-scale operation where hydrogen is produced up to 5tH_2/d and is best suited for hydrogen refuelling stations or electricity storage. The hydrogen produced would need to be at high purity for fuel cell use and be compressed up to 520 bar.
- Once hydrogen is produced via pyrolysis or electrolysis, it would then be transported in its compressed gaseous state over roughly 800 km by tube trailer from northeast BC to refuelling stations or storage locations.
- By using the carbon intensity for gaseous hydrogen, for 800 km, 1,880 kg CO_2/t would be emitted.

- In scenario 2, hydrogen production would be up to 50tH_2/d which would be best suited for industrial facility heating loads.
- Hydrogen would be produced on-site via electrolysis or pyrolysis and transported as a liquid via truck around 1200 km.
- Using the carbon intensity for liquid hydrogen transport, for 1200 km, 809 kg CO_2/t would be emitted.

These numbers allow for comparing environmental impacts. Although scenario 1 is 400 km less distant than scenario 2, emissions are 1,071 kg CO_2/t more due to the associated carbon intensities.



Canadian Market Applicability

Methanol

Market Summary:

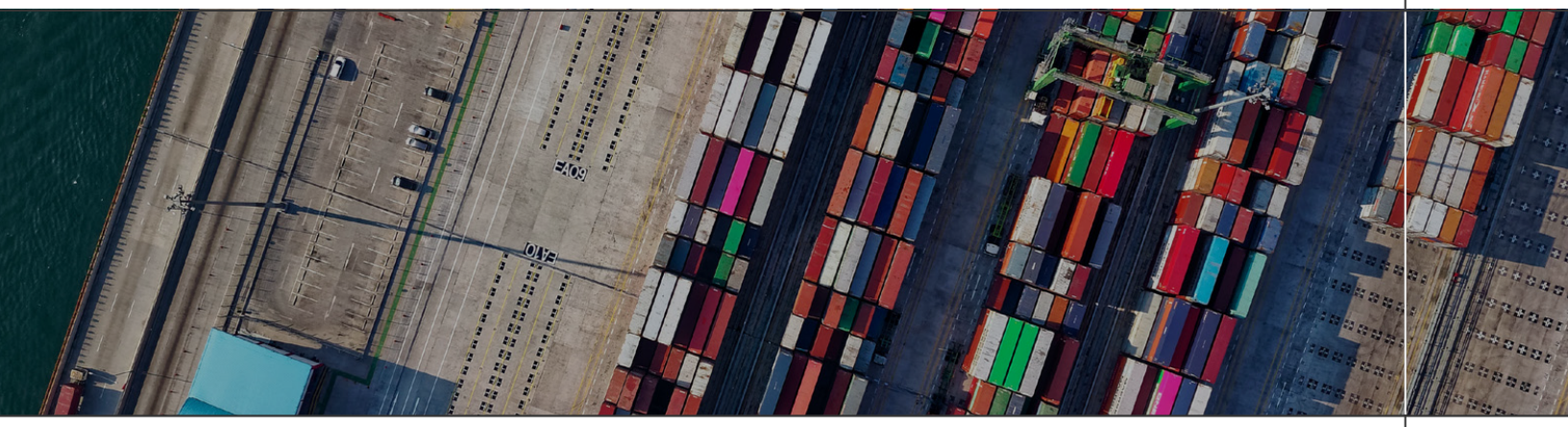
- Global opportunity for use of methanol as a fuel, particularly for shipping.
- One commercial scale methanol production facility in Canada, with several others in proposal/development stages.

Regions of Activity:

- AB, BC, QC

- Market studies have estimated a CAGR of methanol in Canada at 3.7 per cent over the next decade, with an estimated market of approximately 775,000 tonnes. [79]
- There is a global market opportunity for the use of methanol as a fuel, in particular for the shipping industry. Ongoing studies are evaluating the potential for e-methanol production facilities at ports along the west coast of Canada:
  - Major ship lines such as Maersk are leaning into methanol for decarbonizing trans-oceanic shipping.
  - Leading global ports such as the Port of Rotterdam have successfully performed methanol bunkering. [80]
  - A Canadian assessment investigated the requirements and costs of a potential e-methanol plant for the Port of Vancouver; however further assessment is ongoing. [81]
  - Two methanol-fueled tug boats are expected to begin service in the Vancouver harbour in 2025. Methanex subsidiary Waterfront Shipping, based in Vancouver, has a global fleet of 19 deep-sea ships with methanol dual-fuel technology. [82]
  - Carbon Engineering, a Squamish, BC-based DAC company is working with 1PointFive to develop their AIR TO FUELS solution, producing low-carbon fuels, including e-methanol, using captured atmospheric CO_2. Note: all current projects are located in the US. [83]

- Canada has one existing commercial-scale methanol production facility in Medicine Hat, AB (Methanex):
  - In July 2024 Methanex and Entropy announced a partnership to conduct a pre-FEED study into the potential to utilize captured CO_2 in their Alberta production facility. [84]
  - In 2023, Methanex conducted a technical and economic feasibility study to explore the potential to incorporate e-methanol production at existing plants.
  - Methanex has announced further feasibility analysis into e-methanol production at their US and Egypt facilities beginning in 2024, due to the advantages proposed by local incentives. The 45V tax credits under the US Inflation Reduction Act (which provide support for renewable hydrogen production) and the availability of competitively priced renewable power and sources of CO_2 in Egypt along with its proximity to Europe present as the most advantageous for the company. [85]
  - This shows further indication of the economic feasibility of e-methanol being dependent on the price of electricity and CO_2.
- There are additional proposed methanol production facilities in Canada at various stages of development including:
  - Inter Pipeline, Petronas Canada and ITOCHU Japan blue ammonia and blue methanol facilities in Strathcona County, AB (awaiting final investment decision in 2024) [86]
  - Northern Petrochemical Ammonia and Methanol Production Facility in Grande Prairie, AB (proposed) [86]
  - Canadian Methanol Corporation (Renewable Hydrogen Canada Corporation (RH2C)) e-methanol/blue methanol production facility in Tumbler Ridge, BC (feasibility/pre-feasibility) [87]
  - Enerkem Varennes Carbon Recycling biorefinery in Varennes, QC (under construction) [88]



Nitrogen-based Fertilizers

Market Summary:

- All Canadian facilities currently use captured process CO2 emissions.
- No current capture of flue gas CO2 but is a major emissions source that will need mitigation.

Regions of Activity:

- AB, MB, SK, ON

- Canada has nine nitrogen-based fertilizer production facilities in ON, AB, MB, and SK, producing approximately 4.8 million tonnes of ammonia annually. [43]
- Eight of nine produce ammonia through SMR from natural gas feedstock. One uses hydrogen and nitrogen delivered via pipeline from nearby petrochemical facilities.
- Facilities include: [43]
  - CF Industries—Courtright, ON
  - CF Industries—Medicine Hat, AB
  - Koch Fertilizer Canada—Brandon, MB
  - Nutrien—Carseland, AB
  - Nutrien—Fort Saskatchewan, AB
  - Nutrien—Joffre, AB
  - Nutrien—Redwater, AB
  - Sherritt Int. Corp.—Fort Saskatchewan, AB
  - Yara Belle Plaine—Belle Plaine, SK
- Captured process CO_2 emissions from ammonia production are often used by facilities downstream to produce urea. Process emissions are on average, more than 60 per cent of a given facility's emissions, and 61 per cent of process emissions are already recovered, with the majority used for urea production. [43]
- According to Fertilizer Canada, all ammonia facilities using SMR capture a portion of process CO_2 emissions for beneficial use, including: [43]
  - Urea feedstock
  - Use in local greenhouses
  - Sale to gas suppliers or liquefaction facilities
  - Sequestration in ACTL

- Flue gas CO_2 is also a major emissions source from fuel combustion. CO_2 capture of flue gas is not currently used in the Canadian fertilizer sector. [43]
- Listed fertilizer facilities in MB, ON, and SK are not close to any existing CCS infrastructure (Table 1).
- All facilities in AB are close to existing CCS infrastructure (Table 1).

Polymers and Plastics

Market summary:

- Opportunity for use of captured CO_2 to produce renewable plastics. No current Canadian projects.

Regions of activity:

- ON

- Canada's "Chemical Valley" in Southwestern ON around Sarnia is home to a cluster of refineries that produce petrochemicals and plastics.
- Three big plastic producers include Imperial Oil, Nova Chemicals, and INEOS Styrolution. [89]
- Virgin “primary” resin domestic output accounts for $10 billion CAD annually. [90]
- "Renewable plastics" can be produced by combining low-carbon hydrogen and captured CO_2 to make plastic precursors: [91]
    - Commercial projects do exist in the market, however, there are currently no Canadian projects.
    - Ex. LanzaTech CarbonSmart Technology can use captured CO_2 to make ethanol, which can be converted to various chemicals, including polymers/plastics. [92]
- Southwestern ON also has a large emissions cluster, largely due to the petrochemical refining and chemical production industries. Studies have recently shown the presence of some storage geology adjacent to the Great Lakes, specifically the north shore of Lake Erie and parts of Lake Huron; however, there is currently no existing CCS infrastructure in or near ON (Table 1).

Cement and Aggregates

Market Summary:

- Low-carbon concrete is a mature CO2 utilization technology with several leading Canadian companies.
- Recent policy mechanisms intended to support procurement of low-carbon concrete indicates a potential for growing market demand.

Regions of Activity:

- ON, BC, AB

- Low-carbon concrete is a mature technology with some at a commercial stage. There are several examples of leading Canadian companies in this sector such as CarbonCure and Carbon Upcycling Technologies.
  - Canada is home to 12 per cent of CO_2 mineralization projects. [6]
- The economics of low-carbon concrete are challenging to justify; however, the implementation of numerous policy mechanisms to mandate the procurement of low-carbon concrete suggests a future market (see policy barriers and requirements section).
- Canada's cement and concrete industry has released a roadmap and action plan for net-zero emissions. [47]
  - Global demand for concrete is expected to continue to grow, yet cement manufacturing is carbon intensive, accounting for about 1.4 per cent of Canada's total emissions. [47]
  - Enabling measures in the action plan to reduce emissions includes CCUS development, and collaborating with the federal government to support procurement of low-carbon concrete and concrete products, indicating potential growth in demand. [47]
  - Therefore, it can be inferred that there will be an increasing need for concrete, an escalating pressure to decarbonize, and an increase in demand for low-carbon concrete over the coming years.
- There are established cement industry emissions clusters in ON, BC, and AB. The 15 cement plants in Canada are owned by five vertically integrated companies: Ash Grove, Federal White Cement, Lafarge, Heidelberg Materials, St. Marys Cement, and Votorantim Cimentos.

Solid Carbon

Market Summary:

- Permanent carbon sequestration; however, small market projections.

- Solid carbon materials are advantageous as a permanent form of sequestering carbon that require less energy inputs than other pathways discussed in this report.
- Its main use is as a rubber reinforcement in tires; other uses include the manufacturing of coatings, plastics, inks, UV stabilization, pigmentation and mechanical rubber.
- The market for carbon black is about 13 Mt per year, and with demand from current uses could be expected to grow to about 20 Mt by 2050.
- Emerging markets for solid carbon forms including graphite (e.g., in fuel cells, batteries), graphene (e.g., in batteries, solar cells, and electronics), carbon nanotubes, and carbon fibres may positively influence demand in time.
- However, the market is limited if methane pyrolysis becomes a more prevalent process to produce hydrogen–more carbon black will be produced than is needed globally.

Policy Barriers and Requirements

The following section provides insight into the federal and provincial policy and regulatory mechanisms impacting CO_2 utilization. It further lays out the impact of policy on the utilization market and identifies barriers and regulatory uncertainties at the national level.

Federal and Provincial Policy and Regulatory Requirements

Carbon Management Strategy

The Federal Carbon Management Strategy lays down five priority areas for the government to grow a thriving carbon sector in Canada. The five priority areas are accelerating innovation and Research, Development and Demonstration (RD&D), advancing policy and regulation, increasing investments and trade opportunities, scaling up projects and infrastructure, and building collaboration and a skilled workforce. [38]

Budget 2021

The 2021 Budget has committed to providing $319 million over seven years to support the RD&D of CCUS technologies. The funding will be disbursed through Natural Resources Canada (NRCan) via the Energy Innovation Program and will be through a series of funding calls. The object of the funding is to improve the commercialization of carbon management technologies. The fund will support businesses, academia, non-profit organizations, governments and 14 labs across Canada. [38]

Investment Tax Credit for CCUS

The Investment Tax Credit (ITC) provides a refundable tax credit for investments made in CCUS. The rates of the tax credit are based on the type of technology and are split into — 60 per cent for Direct Air Capture (DAC), 50 per cent for capture equipment, and 37.5 per cent for qualified transport, storage, and usage equipment. The investments made between 2022 and 2030 are eligible for a full tax credit rate, and after 2030 until 2040, they are eligible for half the rate and will be phased out after. This is done to encourage early adoption of carbon technologies and is available for investments made in Alberta, Saskatchewan, and BC. [93] CCUS projects aiming to store carbon in geological formations or utilize it in concrete are eligible. [94] To be eligible for the tax credits all CCUS projects must store 10 per cent or more of the captured CO_2 in geological storage or utilize CO_2 in concrete either in Canada or the US, using a qualified process. [95]

Canada Green Buildings Strategy

Natural Resources Canada's Canada Green Buildings Strategy aims to reduce GHG emissions from the building sector by 37 per cent by 2030. [96] The strategy suggests the building sector in Canada needs holistic low-carbon solutions and recognizes that most of those solutions still need to enter the market. A steadily supportive science and technology environment is necessary to develop and establish innovative technologies, materials, and practices that make the result affordable, efficient, and cost-competitive. [96]

Standard on Embodied Carbon in Construction

The Standard on Embodied Carbon requires that emissions associated with new construction be reported and the emission associated with concrete use be less than 10 per cent emission intensive compared to the regional average. [3] This standard applies to major projects, including new construction and renovation using materials like concrete. [97]

Greening Government Strategy

The Greening Government initiative will help with efforts to reduce emissions associated with the construction sector. The Government of Canada spends around $30 billion annually on procurement and is well-positioned to procure products with a low environmental impact and promote clean technologies. All new federal government buildings are required to be net-zero, under the strategy. [98]

Federal Government Funding to UoT

The Federal Government of Canada has provided $1.7 million to the University of Toronto (UoT) and the Canadian Green Building Council (CAGBC) under the Climate Action and Awareness Fund. The funding will support an industry-led research project for CCU approaches and technologies in the concrete sector. It is believed that given concrete is one of the most widely used materials in the world, it could potentially benefit the environment and the economy. [99]

Carbon Contracts for Difference

Carbon Contracts for Difference (CCfDs) help to de-risk the investments made by low-carbon emission industries against uncertain or changing carbon prices. [100] CCfDs incentivize low-emission technology industries by passing the additional costs to the market. [101] In this manner, clean technologies can withstand conventional technologies. [101]

Clean Fuel Regulations

The Clean Fuel Regulations provide incentives for decreasing emissions associated with fossil fuels and the technologies and processes associated with them. The regulations stipulate that the carbon intensity of gasoline and diesel be reduced by 15 per cent by 2030. It applies to producers, sellers, and suppliers of these fuels, and has established a credit market to incentivize low-carbon fuel projects. [102]

Some provinces have also enacted low carbon fuel standards:

Renewable Fuels Standard in Alberta:

The standard requires the fuels produced or imported into Alberta to be blended with renewable fuels like ethanol and bio-based diesel. [103]

Low Carbon Fuel Standard in BC:

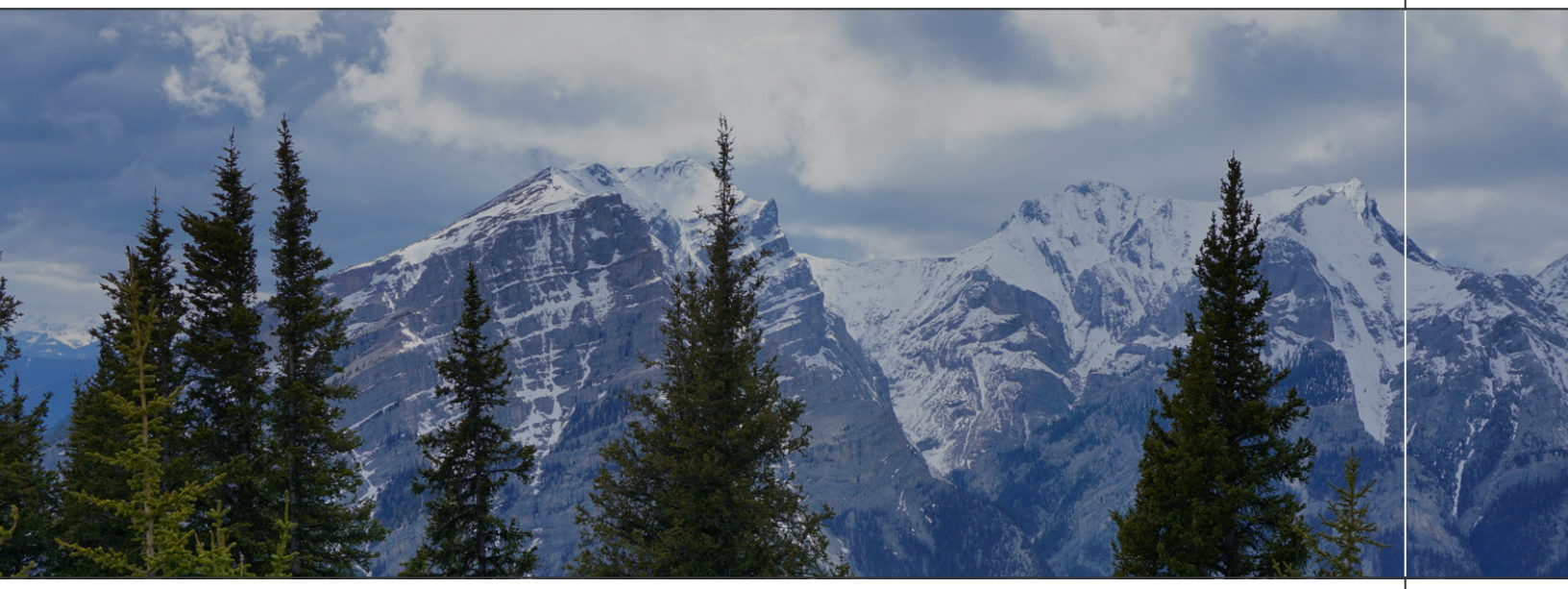
The standard stipulates that fossil fuel-based fuel suppliers reduce the carbon intensity of the fuels each year and combine it with renewable fuels. [104]

Renewable Diesel Act in Saskatchewan:

This act is specific to diesel and stipulates that renewable diesel must be added to the fuel sold in the province. [105]

Cleaner Transportation Fuels Regulation in Ontario:

The regulations stipulate that conventional fossil fuels like gasoline and diesel are to be mixed with cleaner biofuels like ethanol, renewable gasoline, biodiesel, and renewable diesel. [106]



Canada's Pricing on Pollution

The carbon tax puts a price on pollution and pushes businesses to pollute less and offer lower-emission services and products. There are two pricing systems—fuel charge and Output Based pricing System (OBPS). As of 2024, the tax is $\$80/tCO_2$ and has been increasing each year. The federal and provincial carbon tax on gasoline is \$0.1431/L and $\$0.1525/m^3$ for natural gas. [107] The OBPS is a tax levied on industrial emissions and is returned to support lower emission-based projects and clean technologies via the Output-Based Pricing System Process Funds. [108]

Canada Growth Fund

The Canada Growth Fund is a $15 billion public fund encouraging private sector investment in Canadian businesses to reduce emissions and deploy clean technologies. The fund will help speed up the growth of clean technologies like carbon utilization, which will, in turn, benefit the Canadian economy. [109]

Future Market Impact of Policy and Regulatory Changes

The Carbon Management Strategy reveals that the CCUS sector is still in its nascent stage of development, and Canada is looking to grow the sector to meet its emission targets and grow the economy. Moving forward, more targeted RD&D, policy and regulations, and scale-up support can be expected in Canada. This will help develop the entire CCUS ecosystem, including CCS and the carbon-based products market.

A supply surplus of carbon due to excessive emissions could lead to a combination of CCU and CCS. While large quantities of carbon could be opted for geological sequestration, there could still be growth in the utilization sector based on regulatory mechanisms like the CCfDs and the Canada Growth Fund. This is subject to the sufficient deployment of carbon utilization technologies, and in the case there is adequate deployment, we could see several carbon-based products in the market. The carbon-based products will be able to compete with the incumbent products if they are cost-competitive and there is sufficient uptake for such products in the market. Mechanisms like the CCfDs could play a vital role in helping de-risk investments made in clean technologies, and they can enable a market for products made using clean technologies. Products made utilizing captured carbon emissions can compete against incumbent products that may cost less to produce despite the carbon price.

The low-carbon fuel regulations across different provinces in Canada indicate that there is a market for fuels produced using carbon. However, given the multiple renewable fuel options available, we are unable to attest to what proportions and volume of renewable fuels supplied will be from utilizing CO_2. This may still open a use case for carbon utilization in the fuel sector. Similarly, carbon pricing mechanisms in Canada could have an implication on carbon utilization, and we learnt from one of the interview participants that it does not automatically incentivize CO_2 use.

Government construction regulations like the Standard on Embodied Carbon in Construction could lead to CCS and CCU options associated with the cement and concrete sector, which could increase the demand for low-carbon cement and building supplies in the market. This standard utilizes a disclosure mechanism to initiate action. [97] Procurement standards like the Greening Government Strategy signal the market for new low-carbon products, technologies, and construction materials and incentivize action. [98]

Based on the policies and regulations discussed in this section, we can expect the carbon utilization market to grow in the future.

Policy Barriers and Uncertainties at the Federal Level

In the above subsection we saw a number of policies and regulatory mechanisms in place that can directly and in some cases indirectly have an effect on the carbon ecosystem and utilization market. It is also clear from the Carbon Management Strategy that more targeted support can be expected going forward in Canada. However, policy barriers and uncertainties exist in Canada at the Federal level.

Scale Up of Clean Energy

The US Department of Energy (DOE) recognizes that a significant amount of clean energy will be required to support DAC and utilization technologies. This means that a scale-up of clean energy and transmission facilities will be needed to support the deployment of technologies on a life cycle basis. [20] If the current clean energy capacity in Canada is not able to meet the needs to utilize technologies and processes, the market may be affected.

Verification of CO_2- based products

Presently there are no requirements in place to produce net-zero certified products, and there are limited global incentives. This can be deterring especially because the incumbent products that are produced using fossil fuels cost a lot less. [110] Establishing a standardised verification and certification process could help customers make an informed choice.

Targeted innovation policies and regulations

Canada is currently missing some innovative policies and targeted funding support. For example, in the US, the Bipartisan Infrastructure Law (BIL) provides $16.5 billion for innovative projects across the carbon value chain and includes support for projects at pilot and demonstration stages. Under the BIL, the Carbon Utilization Program has allotted $426 million. Other targeted innovation policies include the Carbon Innovative Shot, which specifically focuses on bringing down costs and increasing affordability. [20]

Storage Permanence

An interview participant the team spoke to emphasized the need for a regulatory framework that would address the degree of permanence of carbon stored in carbon-based products.

Addressing these policy and regulatory gaps in the carbon ecosystem can help develop a robust carbon market in the future.

In Conclusion

Utilizing CO_2 is an emerging opportunity. Industrial use of captured CO_2 to manufacture carbon-based products is still nascent, barring a few projects globally, meaning the exact volumes of CO_2 being utilized in Canada are challenging to establish at the current market stage.

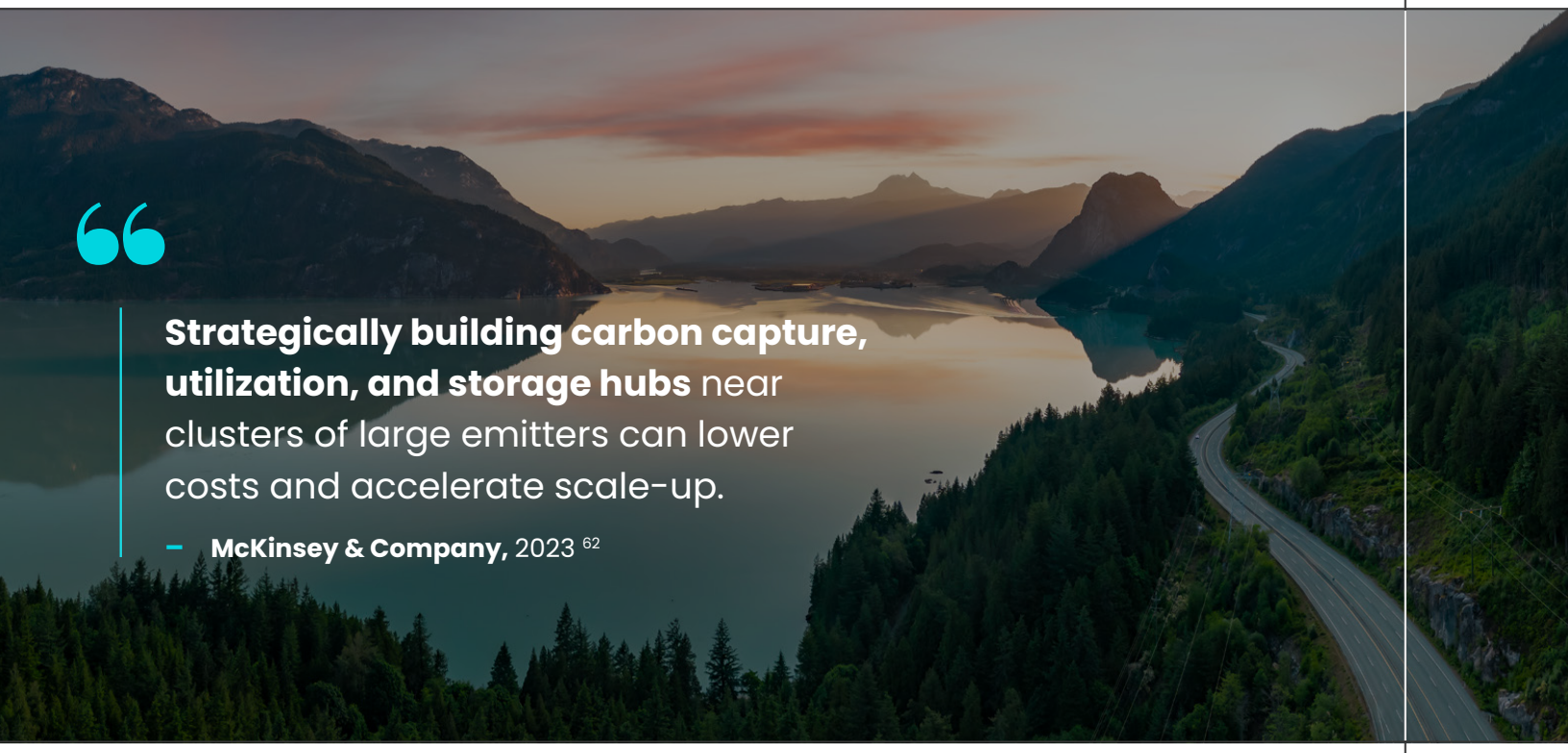
In the short term, the market potential for products and services from captured CO_2 will likely remain relatively small. Future markets for the use of captured CO_2 will likely need high revenues to offset the high cost of capture and conversion. This will have to come either from product value or government policy incentives. There are various projections for the long-term market for CO_2 utilization for 2030 and beyond. As a nascent industry, these numbers are market projections and vary depending on the reference.

Despite the early stage of the market, looking at industrial emissions across the country, particularly in sectors that have been noted as 'hard-to-abate', can help indicate where potential emissions capture technologies may need to be deployed considering emissions reduction mandates. Storage is likely to remain as the leading option, but considering the rationale for using captured CO_2 compared to storing it can then be used to help infer potential future CCU deployment opportunities. Looking at where a point source emitter is located and determining proximity to existing storage infrastructure or storage geology, what available modes of CO_2 transport are nearby, the volume of emissions, and analyzing the cost–which is multivariable itself–among others will factor into the decision-making process.

In Canada, Southwest ON may be a viable opportunity for carbon utilization projects considering the above factors. The absence of a legislative framework around geological sequestration in the province, the presence of several high emitting industrial clusters, a well-established R&D and innovation landscape, and a strong chemical sector that may indicate end-use potential may be worth further exploration.

Ultimately, it is accepted that developing hubs of CCUS activity can make projects more financially viable. Over recent years, large government funding mechanisms for hub development across the US and Europe have signalled this is the direction the industry is heading. [62] Therefore, looking at opportunities to deploy carbon utilization in existing or developing hub regions may be a mechanism to reduce costs by leveraging existing infrastructure and minimal transportation needs. Hubs also co-locate diversified emissions sources and potential end-users for products. The ACTL is an example of an existing Canadian CCUS hub; however, it is currently focused on storage.

While deploying utilization technologies, it is pertinent to consider that different technology pathways are at varied levels of commercialization. Technologies related to the conversion of CO_2 into polymer and chemical feedstock, methanol, carbon nanotubes, and carbon mineralization are near commercialization at various stages. Similarly, technologies related to CO_2 use in concrete are fully commercial and can be deployed. Additionally, as can be seen in the LCA discussion, the carbon intensity of utilization technologies varies immensely depending on feedstock, process, and the composition of the local electricity grid. Conducting a comprehensive LCA considering project-specific parameters is important to gather a fulsome understanding of the emissions mitigation impact of a particular technology.



> **Strategically building carbon capture, utilization, and storage hubs** near clusters of large emitters can lower costs and accelerate scale-up.
>
> – **McKinsey & Company,** 2023 [62]

Next Steps to Accelerate CO_2 Utilization

Canadian industries can play an important role in supporting the advancement and implementation of CO_2 utilization projects. As industry feels increasing pressure to decarbonize from investors, regulators, customers, and more, technologies like CCUS can become an effective tool to reduce emissions, particularly in hard-to-abate sectors. [1] Industry adoption of innovative tech is a critical piece in the commercialization and scale up of CO_2 utilization. However, as a nascent technology, it is perceived as a risk and industry is often reluctant to move forward.

What can industry do to accelerate CO_2 utilization?

1

Knowledge Sharing: Often a misunderstanding of the added value of cleantech, unfamiliarity with the risks of the status quo, and a lack of expertise are contributing factors to the reluctance of adopting a solution. [1] Sharing knowledge by funding the publication of research, collaborating in networks or clusters, and attending conferences can help increase general industry familiarity with carbon technologies, and help avoid the duplication of knowledge-gathering efforts.

2

Pilot Projects: Conducting pilot projects can help to advance the CO_2 utilization market, particularly if multiple companies are involved to lessen and/or share the risk, prove the technology and build understanding and expertise among staff. [2]

3

Collaboration on All Fronts: As discussed above, it is widely accepted that collaborating on CCUS hub development is a way of reducing costs by enabling shared infrastructure. Increased collaboration between industry players is needed to enable the sector to grow. [2]

The future market's success will necessitate the participation and leadership of key industry players to increase investment, drive tech adoption, and eventually, reduce costs. As the market for CO_2 utilization develops, continuing research focused on understanding the most effective role for specific industries is recommended.

As Canada strives to meet climate commitments and transition to a low-carbon economy, industry's continued engagement and leadership in CO_2 utilization will be pivotal. By embracing collaboration and innovation, Canadian industries are not only contributing to national emissions reduction goals but also positioning themselves as global leaders. The success of CCUS in Canada will depend on many factors. Cohesion between industry initiative, government support, and technological advancement will pave the way for a more sustainable future.

Appendix 1: Comparison Table

Comparison Table

Conversion Product	Emerging Technology Needs	Commercialization	Pros	Cons
Methanol (E-methanol)	• Electrochemical and photochemical methods; solid oxide electrolyzer cell (SOEC). • Methods that require lower operating temperature • Reduce the need for costly separation processes to isolate methanol from other reaction products • Development of advanced catalysts for the hydrogenation process • Hydrogen for use as an intermediate in the fuel production process has established alkaline maturity, but is not efficient • PEM and solid oxide electrolyzer cells (SOECs) are early stage, and operate a higher temperatures but have higher conversion efficiency – direction remains unclear	Scale-up and early commercialization	• Versatile product: a fuel, a fuel additive or a base material for chemical products • Established infrastructure for fossil-fuel based methanol • Established safety/ material handling procedures • Can be produced on an industrial scale • Methanol as fuel has higher energy density than liquid H_2 fuel • Few technical challenges with scaleup • Oxygen as a co-product • E-methanol referred to as chemical storage of renewable electricity	• Competition for limited streams of renewable CO_2 and electricity • Need to scale up electrolyzers to supply commercial amounts of H_2 • Currently, e-methanol is 2-3x the price of high carbon intensity methanol – driven largely by electricity costs • Grid electricity in some provinces has high emissions intensity (i.e. AB, SK) • High capital expenditure (i.e. electrolyzer) to produce net zero methanol • Temporary sequestration only – emissions associated with its use
Nitrogen-Based Fertilizers	• Building out required infrastructure such as CO_2 pipelines and a clean electricity grid	Commercial (process CO_2 capture and use) Technology Demonstration (flue gas CO_2 capture)	• Electrolysis can be used to replace steam methane reforming of natural gas feedstock.	• Energy intensive process, requiring a reliable electricity supply as well as access to water. • Steam methane reforming, the steam is a useful by-product for other process units

Conversion Product	Emerging Technology Needs	Commercialization	Pros	Cons
Polymers / Plastics	• Research in bio-based polymers is required • Improvements in biotechnology and electrosynthesis	Scale-up and early commercialization	• CO_2 incorporation can reach up to 50 per cent by mass • CO_2-based polycarbonates are already commercially available	• Temporary sequestration only – plastic products will ultimately degrade • CO_2 is a thermodynamically stable molecule that requires the use of a highly reactive comonomer
Cement and Aggregates	• Availability of low-or zero-carbon fuels to substitute fossil fuels • Newer kiln technologies that increase thermal efficiency • Research and development of new clinker technologies	Scale-up and early commercialization to Commercial	• Considered permanent sequestration • Less energy inputs than fuels pathway • Concrete acts as a CO_2 sink by reacting within the atmosphere to create carbonates	• Mineralization of CO_2 into cement may impact strength, workability, and durability; comprehensive certification and testing required • Common commodity, consumers not willing to pay a 'green' premium • Ionic calcium and magnesium are not available in easy and accessible forms
Solid Carbon	• Limited market: need more demand pull from novel end uses (i.e. for carbon fibres in manufacturing)	Technology Development - Technology Demonstration / Commissioning	• Considered permanent sequestration • Less energy inputs than fuels pathway	• Sourced from oil refining traditionally • Established market players for carbon

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